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CRITERIA OF AGE RELATIONS OF MINERALS. WITH ESPECIAL REFERENCE TO POLISHED SECTIONS OF ORES.

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CONTENTS.

FOREWORD 562
INTRODUCTION 562
PART I. SIMULTANEOUS DEPOSITION 563
UNMIXING OF SOLID SOLUTIONS 566
Definition of terms 566
Types of exsolution textures and their recognition 568
Grating or Bladed type 568
Mottled type 570
Graphic type 571
GRAPHIC INTERGROWTHS 571
PART II. SUCCESSIVE DEPOSITION 576
DEPOSITION IN OPEN SPACES 578
REPLACEMENT 586
General rules for replacement 588
Evidences of replacement 590
Selective Association 594
Pseudomorphism 594
Transection of structures or textures 596
Localization along structural or textural features that should serve to guide the penetration of solutions .. 597
"Islands" in parallel orientation with other "islands" and with the adjacent "mainland." 599
Form of the guest-host contact 600
Contrasting types of replacement 602

Special features bearing upon replacement 604
Residuals 604
Inclusions 604
Mutual boundaries 604
Notable disparity in size among component species 605
Graphic intergrowths 605
Criteria for distinguishing hypogene from supergene replacement 607
Composition of the replacing minerals 607
Replacement by one mineral *vs.* mineral aggregates 608
Depth relationships 610

Foreword.

The determination of the relative ages of the minerals in ores is a matter of first importance to students of ore deposits, since upon it often hinges the diagnosis of the mode of origin of the deposit. Upon some criteria of age relations—particularly of simultaneity—there is still much diversity of opinion; other criteria have been more or less tacitly accepted without in all cases being critically scrutinized and clearly formulated. In the belief that a critical examination and carefully considered statement of these criteria would be of value to students of ore deposits, a sub-committee of the National Research Council on Mineral Paragenesis was appointed, consisting of those whose names appear at the head of this report. The following report is the outcome of many spirited conferences and much correspondence. Although the members of the committee differ with respect to certain points, they are willing that the report in its present form should be presented as a stimulus to further discussion, but carrying no note of finality for themselves or for others.

Introduction.

The precipitation of minerals from any complex solution is governed by composition, concentration, temperature, pressure and time. Changes in any of these factors may result in precipitation. The composition and concentration of the system will change by continued precipitation; they will also be changed by introduction of new materials, *i.e.*, by the adding of solutions or by the reaction of the solutions on solids such as the wall rocks of ore bodies. Thus, even in a single period of primary mineralization, changing conditions may result in age diversity among the ore minerals. In many ores notable age differences among the minerals result from distinct episodes of hypogene mineralization or from the secondary effects of oxidation and downward enrichment.

The secure recognition of contemporaneity or of age diversity among the minerals of an ore is of the highest importance in determining the sequence in which the minerals were deposited and hence in interpreting the genesis of the ore deposit. In the following pages the writers have attempted to formulate and to evaluate somewhat critically the criteria which they and other workers have found useful. In so doing they disclaim any suggestion of finality in their conclusions, but hope that others will be encouraged to supplement them and if need be correct them by the results of their own experience.

PART I. SIMULTANEOUS DEPOSITION.

GENERAL.

That the term simultaneous deposition has been used by geologists in somewhat diverse senses is indicated by such expressions as "partial simultaneity," "essentially simultaneous," or "complete simultaneity." The writers believe that it would be in the interest of clarity if the term were used in the description of ores in its narrow sense, *substances being considered to be simultaneous only if their precipitation from solution begins and ends at the same time.* It is recognized that under natural conditions simultaneous deposition, as so limited, is probably comparatively rare. It is recognized also that overlap is partial simultaneity and that the evidence of overlap consists, in the last analysis, of evidence of simultaneous deposition in one part of the specimen and of successive deposition in an adjacent part. Where overlap can be shown to exist it should preferably be described under the caption of "overlap" rather than "partial simultaneity." It is a common relationship in ores in contrast to the rarity of simultaneous deposition.

The age relations implied in the terms (a) simultaneity, (b) overlap, and (c) successive deposition, as recommended and used in this report are expressed diagrammatically in Fig. 1.

Positive evidence of simultaneous deposition or contemporaneity is in general difficult to secure, and in most cases simultaneity has been doubtfully and tentatively inferred from the

absence of any evidences of age diversity. As indicated later, the so-called "mutual boundaries" are not safe evidence of contemporaneity. Certain minor textures due to unmixing of solid solutions may afford positive evidence of contemporaneity of their components.

Upon the basis of laboratory and field experience simultaneous

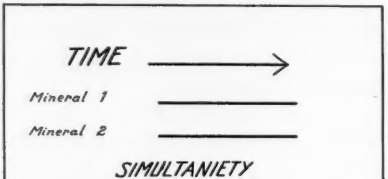


FIG. 1. Diagram illustrating uses of terms Simultaneity, Overlap, and Successive Deposition, in this report.

deposition might be expected under several conditions which may be briefly considered.

a. In the concentrated aqueous solutions of mixed bases as dealt with in the laboratory, the addition of a precipitating agent usually results in the simultaneous precipitation of several components, *e.g.*, metallic chlorides or sulphides. This implies that equilibrium is rapidly established. Where under natural conditions precipitation is brought about by contact with precipitating

agents such as hydrogen sulphide, similar simultaneous precipitation may likewise result, but overlap may also occur.

If the precipitate is definitely *crystalline*, then upon drying and hardening the compounds will form an allotriomorphic aggregate. If there is any marked difference in the power of crystallization those constituents with the stronger power will tend to stand out like phenocrysts.

If the precipitate is *colloidal*, the various compounds, *e.g.*, sulphides, will be intimately mixed. Upon drying and hardening an allotriomorphic crystalline aggregate will commonly result. Here again a somewhat phenocrystic texture may result if certain of the new products have a stronger crystallizing power then others.[1]

b. In artificial dry melts the components generally separate in one orderly succession mainly dependent upon temperature and composition. The periods of deposition overlap and are not simultaneous. However, with rapid cooling the texture may become so fine-grained that evidences of overlap are obscure. Similar conditions probably obtain in the crystallization of many magmas.

c. In artificial *two component* melts that are slowly cooled, the last part will commonly develop as a eutectic, both components crystallizing simultaneously or with slight overlap with characteristic eutectic texture. Intergrowths of such origins are seldom if ever seen in ores.

d. It is well known that in both artificial and natural systems of *more than two components*—one of which may be water—intergrowths resembling the eutectic may form. Familiar examples in pegmatites are the so-called graphic intergrowths of orthoclase and quartz, muscovite and quartz, or tourmaline and quartz. In ores it is probable that the development of eutectic-like intergrowths of antimony and arsenic (allemontite) in colloform masses are an example.[2] Eutectic-like intergrowths of

[1] It is possible that the crystals of cobaltite occurring at Cobalt, Ontario in masses of fine-grained arsenides are the result of such processes.

[2] It is possible, however, that these have formed by simultaneous crystallization from a colloidal precipitate of mixed composition or by the unmixing of a solid solution.

silver and copper in the Lake Superior copper ores are another probable example. As previously explained, some such eutectic-like textures may indicate simultaneous deposition but others probably do not.

e. Simultaneous deposition may be effected by the unmixing of solid solutions. When a mineral *A* crystallizes at temperature *T* as a solid solution, a lowering of the temperature to *t* may result in its breaking up into two minerals *B* and *C*. A nickel-bearing pyrrhotite may break up into pyrrhotite free from nickel, and pentlandite. Textures that have been attributed to unmixing, as observed under the microscope, are commonly marked by plates, dots or dashes, or small crystals, *e.g.,* argentite in galena. The unmixed minerals appear to have formed along cleavage faces or crystal faces or grain boundaries.

Distinction between unmixing effects and replacements may be difficult, *e.g.,* chalcopyrite in sphalerite. Some effects now claimed as unmixing are really caused by replacements.[3] Jamesonite may, for instance, replace sphalerite in minute needles all through the mass.

UNMIXING OF SOLID SOLUTIONS.

Definition of Terms.

If an alloy of copper with a relatively small amount of zinc is allowed to solidify, microscopic examination shows that it is apparently homogeneous in composition and its properties differ only slightly from those of pure copper. If a series of other copper alloys with progressively increasing proportions of zinc (not exceeding 35 per cent.) are prepared and studied, it is found that each alloy is homogeneous and that their properties depart from those of pure copper in a progressively larger degree as the zinc content increases. Such homogeneous solid alloys whose properties vary progressively with varying composition are termed *solid solutions*.

The limits of solid solubility in alloys vary with the nature of the components, with temperature and probably also with pressure. In general the solubility increases with increase in temperature

[3] W. H. Newhouse, ECON. GEOL., 21, 1926, p. 68.

although a few exceptions are known. If, therefore, a solid solution is near saturation with respect to one component at temperature T and the temperature declines to t, a separation of that component may take place. Various terms have been applied to this separation such as "breakdown," "segregation," "unmixing," "transformation," "precipitation" and "exsolution." Objections to some of these terms are apparent as they are more commonly used in connection with other processes. In metallography the term "unmixing" is used by many authorities. The term "exsolution" seems to have found favor lately in geologic publications. Both "unmixing" and "exsolution" can be used with a minimum of confusion and both will be used interchangeably in this report.

In alloys one or both of the components resulting from unmixing may be (*a*) metals, (*b*) compounds, or (*c*) solid solutions.

The interpretation in recent years of certain textures observed in *ores* as due to the unmixing of solid solutions was based originally upon the close resemblance of such ore textures to the textures known to result from unmixing in alloys. The argument by analogy is of course strongest in the case of such intergrowths as those of magnetite and ilmenite in titaniferous iron ores, for these, like the alloys, are solidified melts—although highly complex. Fortunately also this interpretation has received experimental support from the work of Ramdohr,[4] who has shown that intergrown magnetite and ilmenite merge to form a homogeneous solid substance above 800° C.

The applicability of the exsolution interpretation to similar textures in ores that have not formed from melts is less obvious. Here again, however, the interpretation receives support from experimental work, for Schwartz [5] has shown that certain natural

[4] Ramdohr, P.: Beobachtungen an Magnetit, Ilmenit, Eisenglanz und überlegungen das system FeO, Fe_2O, TiO_2. Festschrift zur Jahrfeier der Bergakademie Clausthal, 1925.

[5] Schwartz, G. M.: Experiments Bearing on Bornite-Chalcocite Intergrowths. ECON. GEOL., vol. 23, pp. 381–397, 1928.

Schwartz, G. M.: A New Intergrowth of Bornite and Chalcocite. ECON. GEOL., vol. 24, pp. 443–444, 1929.

Schwartz, G. M.: Intergrowths of Chalcopyrite and Cubanite. ECON. GEOL., vol. 22, pp. 44–61, 1927.

intergrowths of bornite and chalcocite become homogeneous upon heating to 200° C., but upon slow cooling separate to yield intergrowths somewhat similar to certain exsolution textures characteristic of alloys. Bateman[6] has obtained solid solutions of covellite and chalcocite at temperatures as low as 75° C. Schwartz has also produced intergrowths of chalcopyrite and cubanite by the slow cooling of a homogeneous solid solution of the two minerals.

It appears likely, therefore, that the unmixing of solid solutions with the development of characteristic textures has taken place in certain ores formed hydrothermally.

Types of Exsolution Textures and Their Recognition.

Three main types of textures require consideration in any general discussion of the problem of exsolution processes in ores. These may be designated as (*a*) the grating or bladed type, (*b*) the mottled type and (*c*) the graphic type.

Grating or Bladed Type.—This is the commonest type of a crystallographic intergrowth in which the crystal structure of one constituent controls the distribution of the other. The inclusions may be needles, blades or plates. Rarely they may be wavy on polished surfaces. A characteristic intergrowth of this sort at moderate magnification is shown in Fig. 2. This is an intergrowth of ilmenite and magnetite from a magmatic ore.

At the present time it is not possible to formulate with finality the criteria that serve for the recognition of the grating or bladed type of exsolution texture and for distinguishing it from somewhat similar textures resulting from replacement. The following tentative criteria seem to be justified by the studies thus far made.

1. The inclusions of blade, plate, or rod-like forms are characterized by sharp, smooth boundaries. There is no enlargement where the blades join or cross, on the contrary the blades often contract in width at intersections. Replacement veinlets, on the

[6] Bateman, A. M.: Some Covellite-Chalcocite Relationships. Econ. Geol., vol. 24, pp. 424–439, 1929.

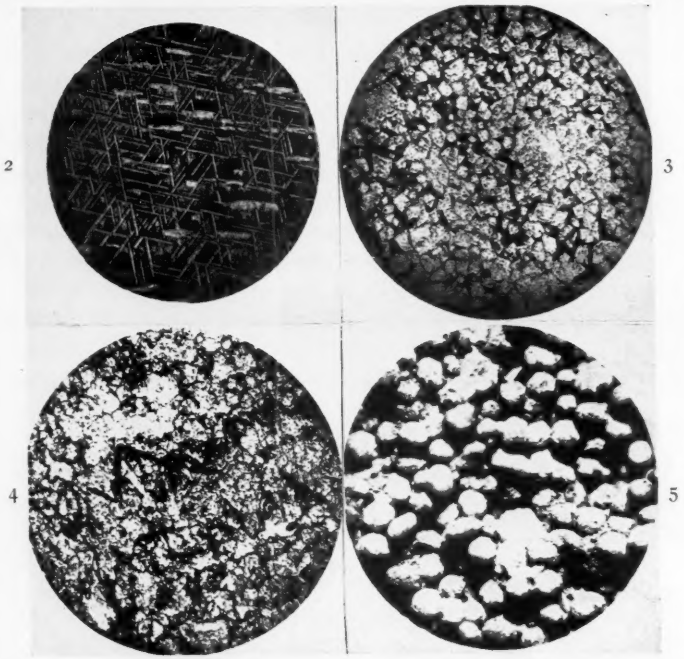


FIG. 2. Intergrowth of ilmenite (light) and magnetite (dark). Pillsbury Lake, Minnesota. ×70 (Schwartz). A grating or bladed intergrowth interpreted as due to unmixing of a solid solution. If the ilmenite replaced the magnetite crystallographically, there should be irregular outlines and enlargements at ilmenite intersections or junctions. (Cf. Fig. 19.)

FIG. 3. Silicified dolomite, Black Hills, South Dakota (Irving). Photomicrograph, ordinary light. Polarized light shows the rock to be quartz. Rhombic outlines in quartz indicate that the quartz has pseudomorphically replaced rhombic crystals of dolomite.

FIG. 4. Stylolitic structure (jagged black band) preserved in fluorite. Photomicrograph, Spar Mountain, Hardin Co., Ill. (Bastin). Stylolitic structure is developed mostly in limestones and is common in those of Hardin Co. Its preservation in fluorite indicates fluorite replacement of limestone.

FIG. 5. Oölitic texture in weathered chert nodule. Prairie du Chien limestone near Baraboo, Wis. (Bastin). This limestone is prevailingly oölitic and this texture in chert indicates replacement of limestone. ×7.

other hand, characteristically enlarge at their intersections (Cf. Fig. 19).

2. The included mineral usually shows no relation to mineral boundaries, fractures and certain other features that commonly serve to guide replacing solutions. The inclusions tend to be evenly distributed. A general absence of evidences of replacement in an oriented mineral intergrowth suggests the possibility of exsolution. Any positive evidence of replacement becomes evidence against exsolution.

3. Commonly the included mineral is absent outside of the intergrowths.

4. The included mineral often forms disconnected units rather than the networks common in replacements along mineral cleavage.

5. The orientation of the blades, plates, or rods, differs for each grain of the enclosing mineral depending upon the crystal orientation with respect to the plane of the section.

6. General similarity of the components in chemical and crystal structure is *a priori* indication of the possibility of the minerals forming a solid solution at higher temperatures.

Mottled Type.—Microscopic inclusions of one mineral in another have been thought by some to result from exsolution. These inclusions may be rounded or irregular and their distribution may be even or uneven. In some cases they are arranged along crystallographic directions of the host. The minute rounded inclusions of chalcopyrite so common in sphalerite (Fig. 7) have been interpreted as the results of unmixing, as have also inclusions of argentite in galena and of sphalerite in stannite. The latter has experimental support.

It is well known that textures of this sort do form by exsolution in artificial alloys. It seems probable that the similar textures observed in ores are in some cases due to unmixing, but in other cases the inclusions may represent the beginnings of replacement and in still others they may be the residuals of nearly complete replacement. As yet no satisfactory criteria have been formulated for differentiating between the several possible origins of

these mottled textures. Their origin must be judged not from the mottled texture itself but from associated textures.

Graphic Type.—By graphic textures as here used are meant those textures in ores or in rocks that closely resemble the textures developed in artificial alloys by simultaneous crystallization at the eutectic point. The term is used in a purely textural sense and is not intended to connote a particular mode of origin.

In artificial alloys it has long been known that graphic textures may result from the unmixing of solid solutions and Howe [7] has termed the mixtures so formed "eutectoids." He says: "The suffix 'oid' clearly indicates that the eutectoid has the form and other important properties of the eutectic; it keeps the resemblance of the eutectoid to the eutectic before the mind, while it allows us to preserve the initial meaning for eutectic and to distinguish between the two really distinct though related entities." The eutectoid point corresponds to the eutectic point but represents a transformation in a solid state rather than a change from liquid to solid state.

No example of the eutectoid texture seems to be known in ores with any certainty. Van der Veen [8] cites the case of allemonite (AsSb) but does not give his reasons for so classifying it. Complete enough data on the system arsenic-antimony are not available to warrant such a classification. Until more examples are established of graphic textures in ores due to unmixing (eutectoids) it would seem premature to attempt to formulate criteria for distinguishing them from graphic intergrowths of other origins.

GRAPHIC INTERGROWTHS.

The term "graphic" is here used in a purely textural sense defined in the preceding section. No single microscopic texture found in ores has been as much discussed as graphic intergrowths but geologists are still far from agreement regarding their significance. A detailed summary of the views of each author would occupy too much space but the following modes of origin have been suggested:

[7] Howe, H. M.: The Metallographist, vol. 6, p. 249, 1903.

[8] Van Der Veen, R. W.: Mineragraphy and Ore-Deposition, 1925, Fig. 64.

1. Simultaneous deposition of two minerals at the eutectic point.

2. Simultaneous deposition of two minerals but *not* in eutectic proportions.

3. Unmixing of a solid solution at the eutectoid point (see preceding section).

4. Replacement of one mineral by another with little regard to the crystal structure of the host mineral.

5. Recrystallization during contact metamorphism.

The term eutectic, as recently pointed out by Fenner,[9] has been loosely used by many geologists. It will be used here in the original sense recommended by Fenner to indicate the invariant point on the phase rule diagram of a system representing the point at which the composition of the solid phases is the same as that of the liquid, and the whole crystallizes at a fixed temperature.

Are any of the graphic intergrowths observed in igneous rocks and in ores to be regarded as eutectic intergrowths in the restricted sense so defined? Fenner[10] has cogently pointed out that whereas in silicate melts made in the laboratory the eutectic point may be attained, in natural magmas impregnated with volatiles the final

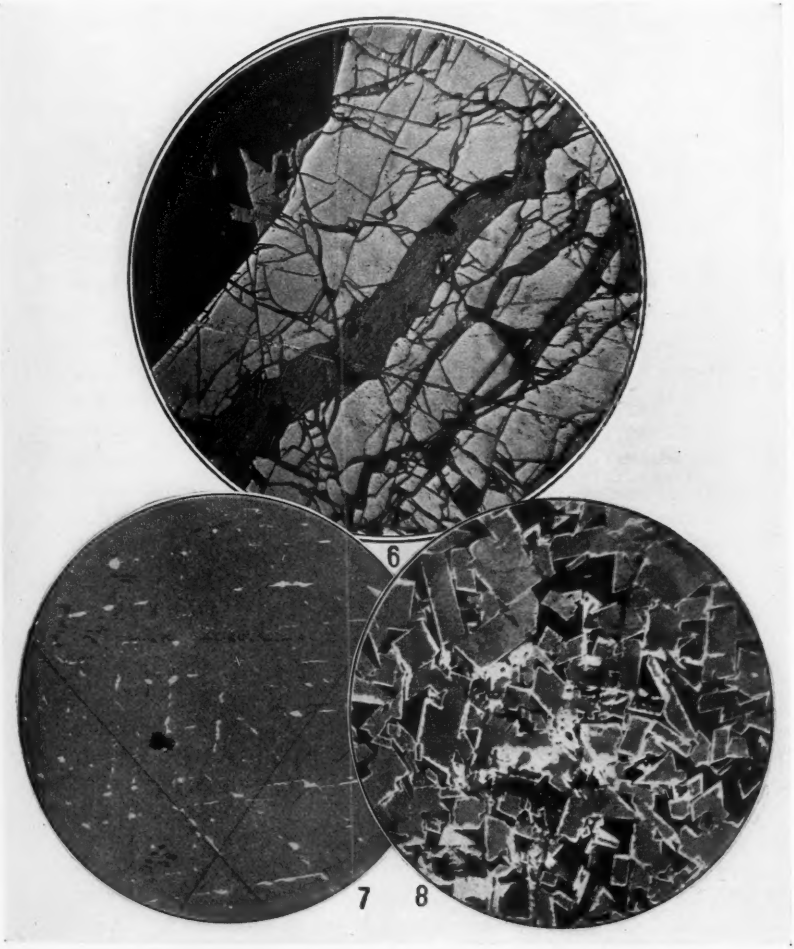
FIG. 6. Chalcopyrite (dark gray) filling fractures in pyrite (light gray). Ruiseñor Mine, near Matahambre, Prov. of Pinar del Rio, Cuba. × 75. (Graton.) The matching of opposite walls of the veinlets indicates fissure filling. These veinlets contrast markedly with the replacement veinlets shown in Fig. 13. whose walls do not match.

FIG. 7. Chalcopyrite in Sphalerite. Probably oriented along cleavage. Hollinger Mine, Ontario. × 250. (Graton.) Intergrowths of this sort have been interpreted by some as due to the unmixing of a solid solution, and by others as due to replacement. Both interpretations may be correct in different instances and no criteria have been formulated for distinguishing between these two possible origins.

FIG. 8. Preservation of the original outlines of brochanthite crystals (gray) in spite of partial replacement by cuprite (white). The peripheral position of the cuprite and its ragged contacts against brochanthite are additional evidences of replacement. Searchlight, Nevada. × 393. (Graton.)

[9] Fenner, Clarence N.: The Significance of the Word "Eutectic." Jour. Geol., vol. 38, pp. 159–166, 1930.

[10] *Ibid.*, pp. 162–163.



FIGS. 6, 7, 8.

crystals are probably deposited not at a eutectic point but "along a boundary curve of decreasing temperature and varying composition until the last of the volatiles escapes or until a more or less dilute aqueous residue of the magma is attained." And further "if two minerals crystallize from a dry melt at a eutectic point in certain proportions, we should not assume without definite evidence that they would crystallize from a plutonic magma or from a pegmatite liquid in the same proportions."

There would appear, therefore, to be reason to doubt whether the graphic intergrowths found in igneous rocks are true eutectics; it is more likely that they are simultaneous intergrowths in other than eutectic proportions, although they may not depart widely from eutectic proportions.

The eutectic character of the graphic intergrowths of metallic minerals found in certain ores of supposedly hydrothermal origin is even more open to question and upon much the same grounds. Furthermore the possibility of a secondary origin must always be considered. Whitehead [11] has pointed out that in a true eutectic intergrowth only one component may be in excess. Examination of the photomicrographs of most of the graphic intergrowths described in ores, especially of chalcocite and bornite, shows both minerals in excess of the possible eutectic intergrowths. They therefore do not represent true eutectic intergrowths; they may however represent simultaneous primary deposition in other than eutectic proportions.

Graphic textures produced in artificial alloys by the unmixing of solid solutions have already been mentioned. No well authenticated instances of graphic textures of a similar origin in ores have as yet been recognized although they are to be expected.

A number of observers, notably Whitehead, Rogers, Guild, Lindgren and Schwartz have interpreted some at least of the graphic intergrowths found in ores as products of replacement. Under this interpretation the two intergrown minerals are regarded not as contemporaneous but as diverse in age. Their interpretations are based upon the presence of specific evidences

[11] Whitehead, W. F.: The Paragenesis of Certain Sulphide Intergrowths. Econ. Geol., vol. 11, pp. 1–13, 1916.

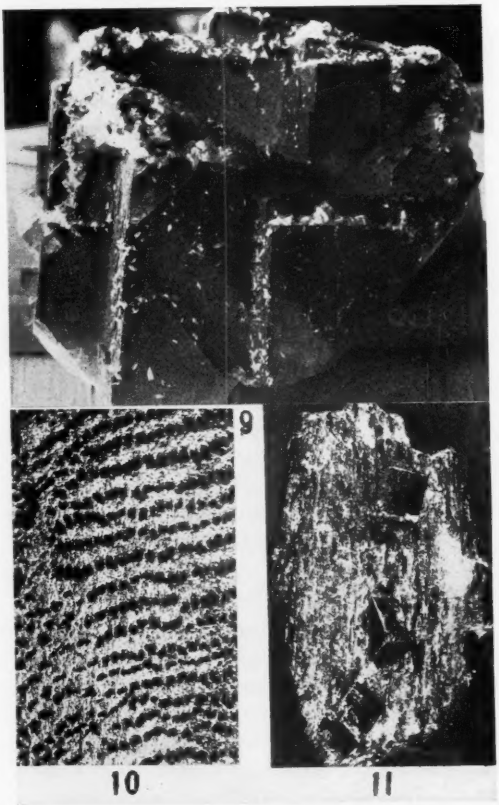


FIG. 9. Calcite crystals (white) deposited on fluorite in vug in Hillside vein, Rosiclare, Ill. The calcite, deposited mainly on upward-facing fluorite surfaces, indicates a gravitational control in its deposition. (Bastin.)

FIG. 10. Pyrite with cellular structure. Pyrite concretion in an Illinois coal seam. × 10. (Schwartz.) The texture indicates pseudomorphic replacement of a plant.

FIG. 11. Transection of schistosity by pyrite cubes. × 4/5. (Bastin.) The perfect pyrite cubes show no distortion and sharply transect the straight schistosity. If the pyrite had been pre-metamorphic, it would have been crushed and distorted and the schistosity would have curved around it; consequently it replaced the schist.

of replacement whose weight can best be evaluated after the nature of replacement and the criteria for its recognition have been discussed. The reader is therefore referred to the subsequent section on replacement for a consideration of this possible mode of formation of graphic textures.

Finally, Schwartz has found evidence of the development of graphic intergrowths of quartz and feldspar in a graywacke by recrystallization during contact metamorphism. No analogous cases have, however, been described from ores.

In general, it appears that at the present time we are not in a position to diagnose the mode of origin of graphic textures found in ores from their inherent characteristics but must rely upon the evidence of associated textures or base our interpretation on geological or geochemical evidences.

PART II. SUCCESSIVE DEPOSITION.

GENERAL.

The methods of reasoning employed to prove successive deposition may be conveniently classified under two types:

I. Indirect geological or geochemical evidence.
II. Direct textural or structural evidence.

This division is not without overlap, however, since geologic concepts usually underlie even the textural and structural evidences. The first type of evidence rests upon the *à priori* postulate that for the formation of certain minerals and rocks markedly different environmental conditions (*e.g.*, temperature, pressure, solution composition, etc.) are necessary, than for the formation of others. This postulate is amply justified by a great body of observational data on mineral and rock occurrence, checked and supplemented by a lesser amount of laboratory data on mineral and rock synthesis. From such data we know definitely the conditions under which certain rocks have formed and it has also become possible to formulate a classification of minerals in accordance with their conditions of formation as first emphasized by Lindgren [12] and later by W. H. Emmons.[13] Many minerals

[12] Lindgren, Waldemar: The Relation of Ore Deposition to Physical Conditions. ECON. GEOL., vol. 2, pp. 105–127, 1907.

[13] Emmons, W. H.: A Genetic Classification of Minerals. ECON. GEOL., vol. 3, pp. 611–627, 1908.

may form through a considerable range of environmental conditions but it is clear that others form only through a comparatively narrow range.

When minerals or rocks that require for their formation notably different environments occur associated, the inference is justified that a change in environmental conditions ensued after one and before the other formed, and hence that they are of diverse ages.

An example of the use of this type of evidence in the case of ore minerals is afforded by associations of galena and anglesite. Although galena is deposited in nature under a wide range of conditions, it is not known to form under oxidizing conditions such as characterize the zone above the ground water level. Anglesite, on the other hand, is known to form only under oxidizing conditions. Furthermore, anglesite is commonly a product of the oxidation of galena. The association of these two minerals implies, therefore, a shift to highly oxidizing conditions after the deposition of galena and before the deposition of the anglesite—and therefore implies age diversity. Other familiar examples are the presence of garnet crystals in limestone and of calcite in the vesicles of basalt.

Evidences of this type when used alone depend entirely for their validity upon the correctness of the geological or geochemical postulates. Fortunately in most cases textural or structural evidences of age diversity are also present.

In nature, rapid precipitation from concentrated solutions is exceptional and equilibrium is usually not rapidly attained. On the contrary, conditions of equilibrium are constantly changing. This constant change is accentuated by the mingling of solutions and the attack upon wall rocks and already deposited material. For such conditions it is evident that chemical laws must be difficult to establish.

Metallic ores, in most cases, are fairly coarse-grained, which suggests relatively slow precipitation. In replacements, however, the newly formed minerals may now and then appear in fine distribution. The various ore minerals are generally deposited in

a well-defined succession and not simultaneously. This succession varies (1) in ore deposits of magmatic affiliations—a very large class; (2) in ores deposited at or near the surface under oxidizing conditions; (3) in ore deposits of sedimentary origin. The succession is best defined in the first of these groups and is to a very important degree controlled by the gradual fall of temperature. For this there is excellent evidence. We may distinguish between (*A*) ores deposited in open spaces, and (*B*) ores deposited by replacement.

DEPOSITION IN OPEN SPACES.

General.—If it can be shown that certain minerals are fillings of open spaces, they must be interpreted as younger than the minerals that bounded these open spaces *at the time of filling.* Amygdules in otherwise unaltered basalt afford an example. Use of this criterion rests upon a previous knowledge of the textures and modes of origin of rocks. Thus, familiarity with vesicular textures and their origin forms the basis for interpreting the origin of amygdaloids. It should be especially emphasized that care must be taken in using this criterion to show that the minerals *now* bordering the filled openings were present at the time the openings were formed and were not developed subsequently. Thus calcite amygdules bordered by the minerals characteristic of basalt may be safely interpreted as younger than the latter but they might be either younger or older than chlorite present as an alteration product in the basalt. Use of this criterion rests therefore upon a knowledge of rock compositions as well as of rock textures and their origins. In short, the history of the rock containing the openings must be known before this criterion becomes applicable.

Not only are fillings of openings significant as indicating age diversity between filling and wall, but sequences in deposition may often be recognized among the filling minerals particularly where *crustification* is present. By crustification is meant the depositing of mineral matter in successive crusts or layers which line the walls of openings. In the absence of evidence of later selective

replacement of certain layers or of later fracturing and filling it may obviously be concluded that the layer next the wall was the first to be deposited. The bands, if crystalline, commonly show comb-structure, due to the parallel elongation of crystals at about right angles to the base of the band.

Ore minerals have been recorded as fillings of the following kinds of openings:

(*a*) Pores.
(*b*) Vesicles and drusy cavities in igneous rocks.
(*c*) Vugs.
(*d*) Solution channels or cavities.
(*e*) Open joints, fractures, and cracks due to cooling.

Deposition in Pores and Vugs.—Deposition in pores is difficult to prove and to differentiate from replacement. Deposition in drusy cavities occurs often in igneous rocks and commonly took place shortly after the consolidation by solutions exuding from the rock; sulphides are not uncommon and may be of slightly diverse ages. In some cases it is probable that the sulphides (*e.g.*, pyrrhotite and pentlandite) filling druses in basic igneous rocks represent liquid residues of relatively low fusibility that separated as a result of limited miscibility and were the last parts of the rock to solidify. Vugs in veins may be filled with sulphides late in the mineralization process. All these occurrences, if interpreted with the cautions that have been indicated, afford definite evidence of age diversity.

Deposition in Vesicles in Lavas.—The filling minerals usually do not crystallize together in allotriomorphic texture, but form definite layers, *e.g.*, chlorite, quartz, calcite, copper, zeolites, the first being the oldest. Falling temperature is certainly one cause of deposition; the composition of the solutions may also have changed. Later minerals may develop by replacement of the older minerals as well as by filling open spaces. Chlorite sometimes develops in basic lavas by replacement and may closely simulate amygdules. Sulphides are rare in amygdules.

Deposition in Solution Cavities.—Such deposition is generally above the water level in air-filled cavities and oxidized ores usually

result. Colloidal precipitates are extremely common with development of limonite, psilomelane, malachite, etc., as stalactitic or colloform deposits. A characteristic of these colloidal deposits is the rapid changes of material corresponding to the various colloids deposited. Stalactites of sulphides are not common but occur in many lead-zinc deposits formed near the surface and without evident affiliation with igneous rocks. Examples come from Raibl, Wisconsin, Vieille Montagne, and Silesia. Sections of some of these show a rapid variation of thin shells, such as many repetitions of marcasite and sphalerite with marcasite generally on the outside. Others from Raibl and Vieille Montagne show galena in the center followed by sucessively younger deposits of marcasite, sphalerite, galena, sphalerite and marcasite. The succession is here clear and unmistakable. The colloidal deposits were almost immediately recrystallized to

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FIG. 12. Transection of schistosity by a cube of pyrite. Hollinger Mine, Ontario, Canada. × 112. (Graton.) See comments under Fig. 11.

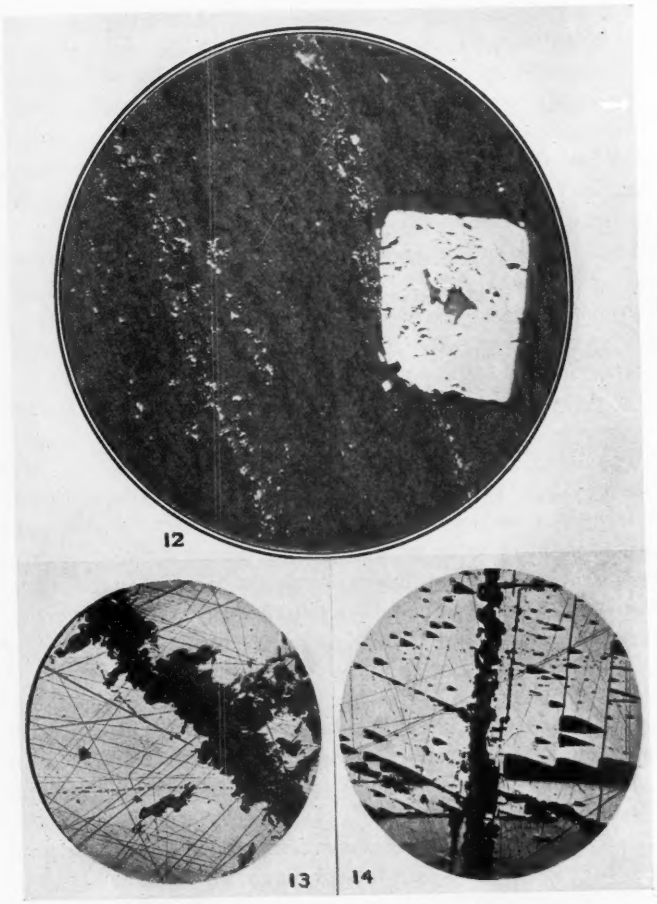
FIG. 13. Veinlet of malachite—a basic carbonate of copper—in chalcocite (Cu_2S). Old Dominion Mine, Globe, Arizona. × 44. (Schwartz.)

The vein form of the malachite indicates that it is younger than the chalcocite it traverses. Geochemical data showing that malachite ordinarily develops under oxidizing conditions whereas chalcocite does not, offer confirmatory evidence of age diversity.

If the malachite veinlet is later than the chalcocite, it may be either a fracture filling or a replacement veinlet. Its irregular outlines with complete failure of opposite walls to match show that replacement is the correct interpretation.

FIG. 14. Veinlets of anglesite ($PbSO_4$) in galena (PbS). Maury Mine, Patagonia District, Arizona. (Bastin.)

The vein form assumed by the anglesite indicates that it is younger than the galena unless the galena itself is a later replacement of some mineral that originally bordered the anglesite. That the anglesite veinlets developed in galena and not in some older mineral is shown by the general parallelism of the anglesite veinlets to galena cleavages. Geochemical evidence that anglesite and galena require different environmental conditions for their formation supports the conclusion of their age diversity. The ragged outlines of the veinlets and the manner in which their opposite walls fail to "match" is evidence that the veinlets were formed by replacement and not by the filling of open fractures.



FIGS. 12, 13, 14.

radial fibrous aggregates except for the galena, which is generally massive. Such colloidal stalactitic layering must not be confused with Liesegang's rings of rhythmic precipitation, which are caused by two later solutions meeting in a gel.

Deposition in pre-existing cavities formed by solution may conceivably be confused with deposition in similar rocks—usually limestones—through replacement. Fillings of solution cavities may usually be recognized by one or more of the following features: (*a*) presence of diversely oriented fragments of wall rock that have obviously broken off the walls of a cavity; (*b*) presence of aggregations of cave earth consisting of the relatively insoluble residue from rock—usually limestone—solution; (*c*) directional deposition controlled by gravity—as stalactites (originally vertical) and deposits on floors of cavities; (*d*) true crustification paralleling the walls.

Deposition in Open Fractures.—Openings formed by fracturing may be very irregular as a result of brecciation or more regular as a result of fissuring. In either case the filling will have sharply defined though often irregular boundaries. Fissure fillings are commonly characterized by walls that "match," *i.e.*, that would fit together at least moderately well if the filling were removed. Perfect matching is not always found, even in fracture fillings, since one wall may have moved with respect to the other in a direction parallel to the plane of the fissure and since fragments torn from the walls in the fracturing may have moved out of the plane of the section available for study. Veinlets that are typical fracture fillings are shown in Fig. 6. The prevalence of matched walls in fissure fillings is in marked contrast to the usual absence of matching in replacement veinlets (Fig. 13). Finally it must be remembered that in the formation of many veins both fissure filling and replacement have been operative and that the effects of each may or may not be separable.

The ores of filled fissures do not ordinarily have allotriomorphic texture. On the contrary the various minerals show an orderly succession which has long been used as a criterion of age disparity. In the rather unusual case where the process results in one single

series of minerals, sometimes symmetrically deposited with reference to the walls, the succession is clearly indicated. But fracturing and repeated openings may obscure the data. Later introduced minerals may replace the older minerals, hence the succession may not always be that indicated by the geometrical relations.

The following remarks on fissure filling refer to those ores which have distinct affiliations with magmatic processes.

The epithermal veins present the best evidence of succession in fissure filling; here crustification is the rule; commonly colloform layers occur in the crusts, indicating colloidal deposits that later crystallized. Some mesothermal veins and a few of the hypothermal type (*e.g.*, certain tin veins) may also show crustification, but a rough banding is more common, or an irregular aggregate caused by replacement of earlier gangue or ore minerals (*e.g.*, gold and tellurides in some quartz veins).

Data on succession among vein minerals have accumulated. One of the best accounts is contained in Breithaupt's "Paragenesis der Mineralien" (Freiberg, 1849). One must admire the wonderful knowledge of the relationship of minerals presented in this book; it will always remain a classic. On the whole, Breithaupt's paragenesis of vein minerals is in accord with our present knowledge, especially as to tin and silver veins, but there are some discrepancies. He thought pyrite was almost always later than chalcopyrite and almost without exception he places galena before sphalerite. At the present time we hold that the reverse is by far the most common relationship. Breithaupt thought much pyrite and marcasite were pseudomorphic after pyrrhotite; this seems puzzling considering the normal reverse succession and the rarity of crystal faces in pyrrhotite.

In almost all cases where crustification is shown the succession begins with quartz and to a greater or less degree the deposition of quartz is later resumed. Usually the successive layers of minerals are pure. There will, for instance, be found repetition of the succession pyrite-quartz-cassiterite. Where one generation rests on the crystal faces of the earlier the succession is clear but if such relations are not found one must always consider the pos-

sibility of later replacements. Repeated deposition is not at all uncommon. Breithaupt mentions a case at Falkenberg in the barytic lead formations where galena was five times repeated, barite 4 times, calcite 3 times, fluorite 3 times, whereas sphalerite occurred in only one band. Here the colloidal mode of deposition seems to be the only likely explanation.[14]

The ores from Parral, Mexico, show the phenomenon of successive, probably colloidal deposition very clearly,[15] and it may be worth while to detail these observations as shown in polished sections, one to two inches wide.

1. Pyrite	2. Pyrite	3 Galena	4. Sphalerite
Arsenopyrite	Arsenopyrite	Pyrite	Quartz and pyrite
Quartz	Quartz	Quartz	Sphalerite
Sphalerite	Marcasite	Sphalerite	Quartz
Pyrite	Quartz	Galena	Galena
	Arsenopyrite	Sphalerite w. specks of chalcopyrite	Quartz with pyrite galena and sphalerite
	Marcasite	Pyrite	Sphalerite near top filled with specks of chalcopyrite
	Quartz	Sphalerite w. pyrite	Galena
	Pyrite	(This succession crossed by quartz veinlet lined with 1. pyrite; 2. sphalerite with pyrite in specks.)	Pyrite
	Marcasite		Quartz
	Sphalerite		
	Pyrite		
	Sphalerite		

The colloform mode of deposition indicates low temperature, as does likewise the presence of marcasite. In (2) pyrite or marcasite was deposited seven times, arsenopyrite twice, quartz four times, sphalerite twice. One specimen shows a residual mass of sphalerite plainly replaced by galena.

Plainly, great caution must be exercised to recognize reopening of veins and later replacements in the already deposited vein material. It is certain, however, that periods of deposition over-

[14] See also Beck, Richard: Lehre von den Erzlagerstätten, vol. I., 1909, p. 245, fig. 137, where concentric barite is deposited on galena.

[15] Thesis of R. K. Doten, Mass. Inst. of Technology, 1929.

lap considerably. It is not possible to conceive of the solutions changing their composition radically for the deposition of each layer. Rather the succession is to be interpreted as caused by delicately changing conditions of saturation in colloidal solutions (for epithermal veins at least). Both quartz and pyrite have a wide range in many cases. One epoch of deposition may be followed by another, which again will begin with pyrite. The wider changes of deposition are probably influenced by sinking temperature. Thus in tin veins the first phase is represented by quartz, pyrite, arsenopyrite and cassiterite; the second by sphalerite, stannite, tetrahedrite; the third by andorite, ruby silver, and jamesonite. In copper veins the general succession may be quartz, pyrite, sphalerite, enargite, tennantite, bornite, chalcopyrite, chalcocite. In cobalt veins the various arsenides are deposited first, and are followed by native silver, argentite, and proustite. In lead veins the succession is commonly siderite, quartz, sphalerite, galena, tetrahedrite, followed by ruby silver, polybasite and other rich silver minerals. Breithaupt mentions an ore from Spain in which sphalerite and siderite were repeated five times. Another common succession is quartz, rhodochrosite, sphalerite and galena, quartz. In gold veins the bulk of the quartz and the principal sulphides antedate the deposition of the tellurides; the gold is usually the last mineral. Of the gangue minerals, barite, fluorite and carbonates are usually deposited most abundantly in the early stages, but may also recur later; calcite is commonly the last mineral.

A characteristic two-phase succession is described by W. H. Newhouse[16] from Angangueo, Michoancan, Mexico, as follows: Earlier phase: pyrite, arsenopyrite, pyrrhotite, galena, sphalerite (later than galena), tetrahedrite and chalcopyrite; later phase: Marcasite, manganosiderite, pyrite, quartz, ruby silver.

Another case where galena is certainly earlier than sphalerite is figured by Beck.[17] Another case where pyrite is later than "black silver sulphides" is described by Spurr.[18] The last two

[16] ECON. GEOL., vol. 20, p. 59, 1925.

[17] *Op. cit.*, vol. I., p. 248, fig. 140.

[18] Spurr, J. E.: ECON. GEOL., vol. 21, p. 524, 1926.

cases represent cockade ore, and are therefore particularly convincing.

Illustrations of filled fissures may be found in figs. 175, 177, 183, 194, 196, 199, 237, 257 of Lindgren's "Mineral Deposits," Third Edition.

Gravitative Control in Deposition.—In some ore deposits the last minerals to be precipitated in vugs or other open spaces clearly deposited under the influence of gravity. Stalactites in the zone of oxidation constitute the most familiar examples of such deposits but other examples are found in the fluorite deposits of southern Illinois, where layers of calcite or of barite crystals coat the upper surfaces of fluorite crystals in vugs but do not coat their sides or downward-facing surfaces. The phenomenon is analagous to the heaping up of snow on the roof of a house and its absence from the walls and under the eaves. Fig. 9 shows these relationships. Such deposits are obviously younger than the minerals they coat that show no relationship to the direction of the force of gravity.

REPLACEMENT.

Introduction.

Where no appreciable open spaces are available which ores may occupy, deposition may be accomplished through replacement. Replacement may be defined as the dissolving of one mineral or group of minerals and the simultaneous deposition of another mineral or group of minerals in their place. Solution and deposition proceed concurrently without the intervening development of appreciable open spaces, and the substitution commonly involves no change in volume. A replacing mineral is termed a metasome. If it assumes its own characteristic crystal outlines it is termed a metacryst.

The replacing solutions make their way along supercapillary to subcapillary openings and replace rock minerals by ore minerals and gangue. They may also replace earlier deposited gangue minerals and sulphides. In recent years a large literature based on the study of replacement has accumulated. The conditions obtaining during replacement differ in degree if not in kind from

those characterizing the filling of openings, for (a) diffusion is a more prominent phenomenon and (b) precipitation is caused in part at least by changes in the equilibrium of the solution produced by the dissolving of the host. It should be emphasized, however, that in the formation of most ore deposits replacement and the filling of openings go on concurrently although either process may dominate. Temperature and pressure are generally much the same where replacement is in progress as in the open spaces of the same environment. If anything, the temperature away from the open ducts would tend to be more uniform. There is, then, a complex series of replacements always exhibiting age diversity but commonly difficult to unravel. A definite succession can, however, usually be established and there is more uniformity and consistency than is obtained by the study of filled fissures. Frequently repeated successions, so common in filled fissures, cannot be established in replacements.

The field observed in polished sections under the microscope shows ore minerals more or less in contact. They are as a rule imbedded in gangue minerals and in country rock, if any of the original host rock remains. There may also be filled veinlets and replacement veinlets not always easy to distinguish from one another; there may also be drusy cavities with local fillings which may help the interpretation. The problem is to ascertain the relation of the various minerals, whether simultaneous or in succession. If the latter, there are then one or more processes to consider *e.g.,* oxidized products, secondary sulphides, repeated series of hypogene ore minerals.

The normal hypogene succession has been established by various authors,[19] and in a general way these results agree.

Studies of age relations in scattered form are found in practically all descriptions of polished ore sections. Lately the subject has been discussed in its more general aspects by W. H. New-

[19] W. M. Davy, ECON. GEOL., vol. 15, p. 491, 1920. W. Lindgren, Trans. Am. Inst. Min. and Met. Eng., vol. 74, pp. 71–92, 1926. W. Lindgren, ECON. GEOL., vol. 22, p. 305, 1927. M. J. Buerger and J. L. Maury, ECON. GEOL., vol. 22, p. 11, 1927. W. Lindgren and J. G. Creveling, ECON. GEOL., vol. 23, p. 254, 1928. F. N. Guild, in Fairbanks, E. E., The Laboratory Investigation of Ores, 1928, p. 206.

house [20] and R. J. Colony.[21] A good deal of diversity of opinion has been expressed and an agreement on all controversial points has not yet been reached.

General Rules for Replacement.

1. " Sulphides " [22] replace all rock minerals, all gangue minerals and all " sulphides."

2. Gangue minerals replace rock minerals and other gangue minerals but do not commonly replace " sulphides."

3. High temperature oxides (magnetite, cassiterite, etc.), replace all rock and gangue minerals but are rarely replaced by gangue minerals.

4. Oxides rarely replace " sulphides."

5. " Sulphides " may replace rock and gangue in all directions, but are commonly guided by fissures and cracks. Control by cleavage planes is not so common.

6. Replacing gangue metasomes, *e.g.*, quartz, tourmaline, barite, fluorite, alunite and iron and magnesium carbonates, may develop as metacrysts in rock minerals. In limestone the tendency towards metacrysts is much stronger than in silicate rocks.

7. Replacing " sulphide " metasomes in the case of some minerals may develop as metacrysts. Such are pyrite, arsenides, enargite and jamesonite; other " sulphides " rarely develop as metacrysts.

8. High temperature oxides often develop as metacrysts.

9. Minerals showing idiomorphic forms in sections of replacement ores may be (1) residual crystals—*e.g.*, quartz, or feldspar phenocrysts in porphyries; pyrite and magnetite crystals in crystalline schists; (2) products of local filling, then often surrounded by later filling material; (3) metacrysts.

10. Rounding of crystals in ores does not necessarily indicate replacement, for similar rounding may be shown by phenocrysts and by crystals deposited in open spaces.

[20] In Fairbanks, Laboratory Investigations of Ores, 1928, pp. 147–161.

[21] *Idem*, pp. 132–146.

[22] " Sulphides " is here used as a general term including sulphides, arsenides, tellurides and sulphosalts.

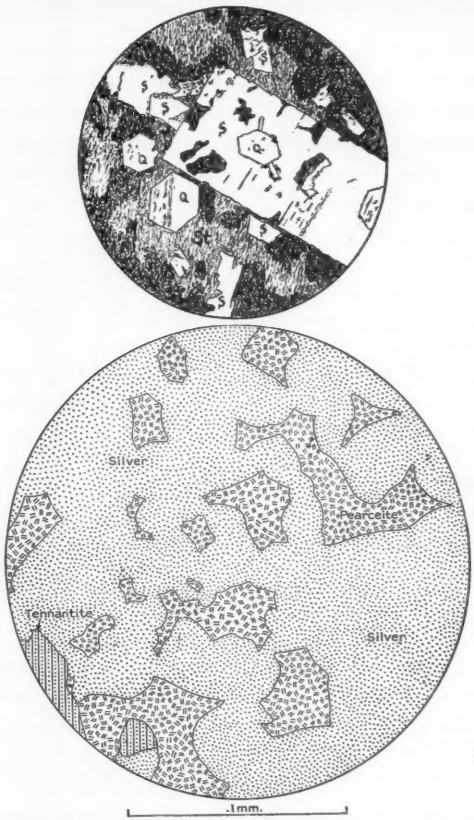


FIG. 15 (Upper). Stephanite in the matrix of a quartz-feldspar porphyry. *Q.*, quartz; *S.*, sanidine; *St.*, stephanite. ×36. Silver Cord Claim, Leadville, Colo. (Fenner.) Since sulphosalts of silver cannot form at the high crystallization temperature of a porphyry, the stephanite must have formed subsequently, at lower temperature, by selective replacement of the porphyry matrix.

FIG. 16 (Lower). Native silver and pearceite. Aspen, Colorado. (Bastin.) Camera lucida drawing. The convex curved outlines of the native silver against the pearceite are inconclusive evidence but commonly result from replacement and constitute confirmatory evidence along with other evidences of replacement. Such contacts with the guest mineral "bitten into" the host are called "caries" by Lindgren. Other Aspen specimens clearly show replacement of pearceite by native silver along the grain contacts.

11. An initial replacement is not necessarily followed by other replacements. Thus, a pyrite metacryst in granite may be perfectly formed and afford *per se* no geometrical evidence of replacement although proofs of replacement origin may occur elsewhere in the section. In other cases the initial replacement is followed by a succession of later replacements. These may attack the earlier metasomes and destroy or impair their crystal outlines or they may affect only the rock minerals and leave the outlines of the early metasomes unimpaired. A thin coating of clay or similar substance may suffice to prevent the attack of an earlier metasome.

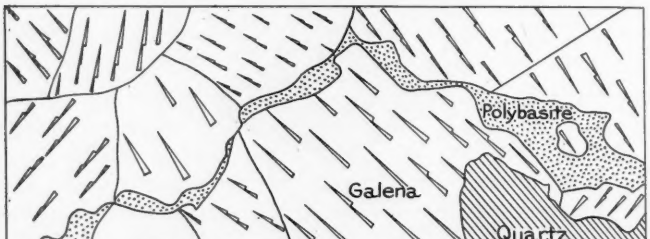


FIG. 17. Camera-lucida drawing from lead-silver ore from Neihart, Montana. (Bastin.) The presence of polybasite along the contacts between differently oriented galena grains, along the contacts between galena and quartz and along cleavage directions of the galena (as at *A*) suggests that it has developed by replacement of galena, for such positions would be channels along which replacing solutions might readily penetrate.

Evidences of Replacement.

General.—In the recognition of successive deposition whether in open spaces or by replacement, evidence of an indirect geologi-

cal or geochemical nature is frequently used. Although such evidence may suffice to establish age diversity, it seldom determines the cause of such diversity—whether replacement or successive deposition in open spaces. For the recognition of replacement other criteria must be utilized.

The recognition of replacement depends most commonly on the recognition of a host structure in spite of varying degrees of modification by later guest minerals.

In most discussions of replacement the importance of the structure of the host has not been sufficiently emphasized. During the process of replacement some or all of the host is removed and a guest mineral or several guest minerals are placed in the space formerly occupied by the host; this may be by pseudomorphism, by veinlets, by irregular masses transecting structures or texture, by localization of minerals along structural or textural features that may serve to guide the penetration of solutions, etc.

It is obviously the host that localizes and guides the guest and it is to the structure or texture of the host that we should look for confirmation of replacement. If one can not pick out such structures or texture in the host, some features of which still remain unmodified by the destroying guest, such as crystal form, banding, etc., the fact of replacement can not be proven except by geological or geochemical reasoning.

Much of the proof for replacement where some relict or arrangement of host structure or texture is used is dependent upon the geometrical or spatial relation of guest and host. But in many examples these geometrical relations, to be considered significant, must be interpreted according to some theory of structural continuity in the host, be the structure that of single crystals, mineral aggregates, or bands of minerals. Therefore, since this theory is always geological or geochemical in nature, it must be concluded that to prove replacement usually, although not always, some elements of geological or geochemical reasoning are present.

For example, in many discussions of "veins" the interest is centered on the supposed guest, but unless the structure or texture of the supposed host can be deciphered, and the contact relations between the vein minerals and this host show clear re-

placement relations, the evidence must be considered inconclusive for replacement unless, as in a large scale vein, geological evidence is used as proof. It must be admitted that certain intergrowths formed by unmixing and others formed by replacement are so similar that no means of distinguishing between them are at present known.

It should be emphasized that a single criterion may or may not

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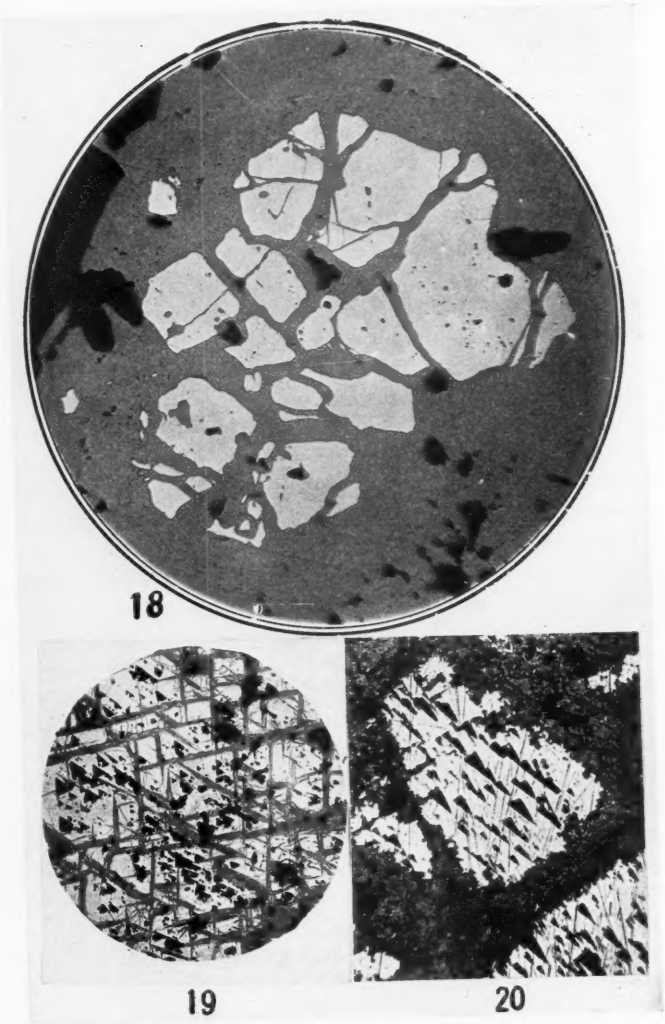
FIG. 18. Pyrite (light gray) in a matrix of bornite (dark gray). Butte, Montana. × 85. (Graton.) The pyrite fragments were originally parts of one large pyrite mass that may have been isolated (*a*) by fracturing with subsequent filling by bornite, or (*b*) by replacement of pyrite by bornite spreading from small fractures, or (*c*) by a combination of the two. If fracturing alone were involved, the fragments should fit together if the bornite matrix were removed; this is not the case. Also, some of the pyrite fragments should be in contact, but such is not the case. The replacement interpretation, however, is supported by the failure in most places of opposite walls of the bornite veinlets to match.

FIG. 19. Veinlets of anglesite (gray) traversing galena (white). Kent Mine, Bannack District, Montana. × 60. (Schwartz.) The vein-like forms of the anglesite indicate that it is younger than the galena which it traverses. The sides of the triangular pits (black) in the galena are parallel to its cleavage directions. The anglesite veinlets also parallel the galena cleavages. The failure of opposite walls to "match" plus the indicated impossibility of mechanical dislocation (faulting) of the two walls relative to one another indicate that they are replacement veinlets rather than fracture fillings.

Note that the replacement veinlets tend to enlarge where they join, in contrast to blades and plates interpreted as formed by unmixing, shown in Fig. 2.

FIG. 20. Association of anglesite (dark) and galena. × 50. Maury Mine, Patagonia District, Arizona. (Bastin.) The triangular pits (black) outline the cleavage directions of the galena. The vein-like form of some of the anglesite, which roughly parallels the galena cleavages, suggests that it is younger than the galena. Anglesite forms normally under oxidizing conditions, whereas galena does not; this is confirmatory evidence of age diversity. The younger anglesite either replaced the galena or filled in between galena fragments. The ragged outlines of the galena areas and the fact that they are in exact crystallographic parallelism indicate that the fragments were not isolated by fracturing. These features are compatible with the hypothesis of replacement controlled in part by galena cleavages but proceeding in part irregularly.



FIGS. 18, 19, 20.

afford conclusive evidence of replacement and that the evidence is strongest when several criteria are applied.

The criteria that have been used for the recognition of replacement may be listed as follows:

I. Geological or Geochemical evidences.
   Selective association.
II. Recognition of host structure or texture that has been modified by later guest minerals.
   Psedomorphism.
   Transection of structures and textures.

Selective Association.—On *a priori* grounds it is to be expected that when a rock (including ores) made up of several mineral species is attacked by replacing solutions, some minerals will commonly be replaced more readily than others. In places, therefore, where replacement is in its initial stages the replacing minerals should be found associated exclusively, or at least prevailingly, with one or perhaps two host minerals. In situations where other criteria indicate that replacement has been operative, such selective associations offer confirmatory evidence.

Excellent examples of selective replacements are found in many of the wall-rock alterations bordering ore bodies. In the case of a granite wall-rock, selective replacement of feldspars by sericite and of biotite by pyrite are common phenomena.

In ores containing both pyrite and chalcopyrite with only minor amounts of chalcocite, the chalcocite is often associated exclusively with the chalcopyrite, and other criteria show that it is a selective replacement of that mineral. Where chalcocite becomes abundant it is associated with pyrite as well as with chalcopyrite. Galena commonly preferentially replaces sphalerite; gold, arsenopyrite; and silver, arsenides and antimonides. The latter two cases have been confirmed by experimental data.

Pseudomorphism.—Pseudomorphism may be defined as the presence in a mineral or mineral aggregate of forms, textures, or structures not characteristic of itself but characteristic instead of other minerals, or mineral aggregates, or even of organisms. This criterion rests upon *a priori* grounds since its use presupposes a

knowledge of forms, textures, and structures of minerals, rocks, and organisms, and of the conditions under which these normally develop. Recognition of the abnormality of pseudomorphism rests, therefore, upon a knowledge of the normal relationships. Pseudomorphism results from the dissolving of one mineral or group of minerals and the depositing of another mineral or group of minerals in its place. Usually the processes of solution and deposition go on simultaneously through the medium of the same solution and without the development of open spaces—constituting the process known as replacement or metasomatism. The most delicate and perfect pseudomorphism is developed in this way. In other instances, however, minerals are dissolved by one solution and after an interval during which open spaces exist, new minerals are deposited in these spaces by solutions of a different composition. This is *not* replacement. Save in exceptional instances it preserves only outward form—*not* internal structure. Since replacement—the dominant process in the development of pseudomorphs—may operate under conditions of high or low temperature or pressure and may affect almost any type of rock, almost any rock texture or structure may at one place or another be preserved pseudomorphically.

The value of this feature as a criterion of replacement is greatly enhanced by the finding of unreplaced remnants of the crystal, bedding, or other structure which has been pseudomorphically preserved.

Features that are on record as preserved pseudomorphically in ores include the following:

Mineral textures and structures.
- Crystal outlines (Figs. 3 and 8).
- Crystallographic orientation.
- Parting.
- Cleavage.

Sedimentary textures and structures.
- Bedding.
- Cross-bedding.
- Stylolithic structure (Fig. 4).
- Form or pattern of grains.
  - Oölites (Fig. 5).

Textures and structures of igneous rocks.
Flow lines.
Form or pattern of grains.
Porphyritic texture (Fig. 15).

Organic structures.
Form of shells, corals, crinoids, etc.
Cellular structure of plants (Fig. 10).

Transection of Structures or Textures.—Although in some cases the structures or textures of the host are preserved through replacement, in others they are obliterated. Even where obliterated it is clear in some cases that the structures or textures once extended uninterruptedly through areas now occupied by certain minerals, and that these minerals have been developed by replacement. Commonly the minerals that obliterate older structures or textures develop their own characteristic crystal faces. Structures and textures thus transected include crystals, typical aggregates of crystals or grains (such as a rock having granitoid texture, or a sandstone), banded structures (such as banded veins), bedding, schistosity, and flow lines; also organic structures, oölites, and amygdules. Where replacement has apparently transected one of the larger structures mentioned, such as a gneiss, the apparent replacement is in reality usually supported mainly by geological evidence as to the origin and relative ages of the host and supposed guest. These large-scale relations may receive support or positive proof from the relations shown by the small units that build up the larger masses, namely, the crystals. These may show transection relations at the guest-host boundary. It is in these smaller scale or crystal relations that much of the proof of replacement is found in the transection phenomena. Perhaps the only type of small replacement vein whose description does not require reservations and qualifications is one of irregular width that transects many diversely oriented host crystals and follows to some extent the cleavage of the host crystals.

It should be emphasized that elongation of a mineral mass is probably too often used as proof that it is a vein. Unless the "vein" relation to the larger unit of structure, such as a granitoid textured host, is clear, also the relation of the small adjoining

units (*i.e.*, crystals or grains at the host and guest boundary), the interpretation may be faulty.

An example of the applicability of this criterion is afforded by the specimens shown in Figs. 11 and 12, in which well developed schistosity is transected by perfect cubes of pyrite that are not fractured. The planes of schistosity must once have extended across the spaces now occupied by pyrite, for had the pyrite been present before the metamorphism of the rock the schistosity would wrap around the pyrite crystals and the latter furthermore would probably have been deformed or at least somewhat fractured. It must be inferred, therefore, that the pyrite cubes developed through replacement after the metamorphism of the rock.

Localization along Structural or Textural Features that Should Serve to Guide the Penetration of Solutions.—Relationships of this sort, although seldom affording conclusive evidence of replacement, have value if supplemented by more certain criteria. The localization of guest minerals along structural or textural features of the host is undoubtedly common but the proof of this fact frequently depends upon other relations.

Features that commonly serve to guide solutions in their penetration of a rock are:

Fractures and other openings.
Bedding planes.
Schistosity.
Contacts between mineral grains of the same or different species (Fig. 17).
Cleavage and parting planes of minerals (Fig. 17).

Although replacement is in many instances initiated from openings of notable size, one of the most striking features of the process is the ability of the solutions to penetrate along directions of schistosity or contacts of mineral grains, where the highest powers of the microscope do not reveal any open channels. From such guiding features the solutions penetrate and replace the bordering minerals.

Minerals deposited by replacement near channels favorable for the penetration of solutions may develop singly or in a zoned

sequence, the minerals of which may show consistent chemical relationships. Thus, about the border of grains of polybasite, there may be developed first a zone of argentite and then a zone of native silver, the sequence being characterized by a progressive increase in silver content. Such zonal sequences are fairly common in ores that have undergone supergene enrichment in copper or in silver. In ores from the Maury Mine, Arizona, galena is bordered first by a zone of covellite crystals outside of which is a zone of anglesite and then a zone of cerussite. They represent a progressive sequence of replacements during oxidation, and the distribution of all these minerals is clearly related to galena cleavage.

Features capable of guiding the penetration of solutions may have originated contemporaneously with the host (*e.g.*, mineral cleavage, bedding, etc.) or they may have originated subsequently (*e.g.*, fractures). Evidence of replacement is often stronger in the latter case. For example, if chalcopyrite is found in gash-like forms paralleling the cleavage of bornite or sphalerite, then, so far as is known at present, the relations could have resulted either from unmixing (exsolution) or from replacement. If, on the other hand, chalcopyrite in vein-like forms occurs along what are clearly fractures in bornite or sphalerite, then unmixing is ruled out, for the chalcopyrite must be later than these minerals. It may, however, have been deposited either by fracture filling or by replacement—a point to be settled by the use of other criteria. Replacement in concordance with the structure of the host is commonly associated with some degree of transection of structure, and the combination of the two gives excellent evidence of replacement.

Veinlets constitute the commonest examples of deposition along fractures and afford one of the best proofs of age diversity. They are features which the worker with polished ores almost instinctively looks for. To be satisfactory the veinlets should be fairly uniform in thickness and they should cut across several grains of different orientation. Veinlets may be fissure fillings or replacements or formed by both processes operating hand in hand. The latter is probably the commonest case. Typical replacement

veinlets are shown in Figs. 13 and 14; a network of such veinlets following galena cleavages is shown in Fig. 19.

Replacement following fractures may tend ultimately to divide the host into irregular fragments, the residuals often looking like a breccia except that they are nowhere in contact (exploded bomb structure). The approximate outlines of the original mass before replacement are commonly obvious from the distribution of the replacement remnants. Pyrite often shows this structure (Fig. 18).

Replacement along fractures is equally common in supergene and hypogene mineralization. The possibility must be considered that the vein minerals may themselves be a replacement of older vein minerals (*e.g.*, bornite veins replaced by chalcocite).

In sediments that show delicate stratification, the replacement by various sulphides may follow selectively certain beds, usually because of some difference in composition of the beds. Pyrrhotite, sphalerite and galena in the ores of the Sullivan Mine, British Columbia, constitute an excellent example.

Replacements along contacts between mineral grains seem to be especially characteristic of supergene mineralizations and proceed from the periphery of the grains inward. They might therefore be termed centripetal replacement (Fig. 17).

"Islands" in parallel orientation with other "islands" and with the adjacent "mainland." [23]—When, as is so often the case, replacement proceeds irregularly, areas of the host may become partly or wholly surrounded by the guest mineral or minerals. In such cases in a polished specimen or on a larger scale on the wall of a mine-working, these isolated areas often present the appearance of "islands" separated from the main body or "mainland" of host material (Fig. 20). In many instances the host shows orientation features such as bedding, cleavage, etc., and the

[23] This criterion is the same as the "unsupported structures" of Irving (1, p. 285). This term has been avoided, however, because in most instances our observations are limited to a single plane transecting the ore. Only rarely is it possible to study relationships in three dimensions and prove that masses of the host were *completely* surrounded by other minerals. Even in such instances the term "unsupported" is of questionable felicity.

"islands" are oriented similarly to neighboring "islands" and to the "mainland."

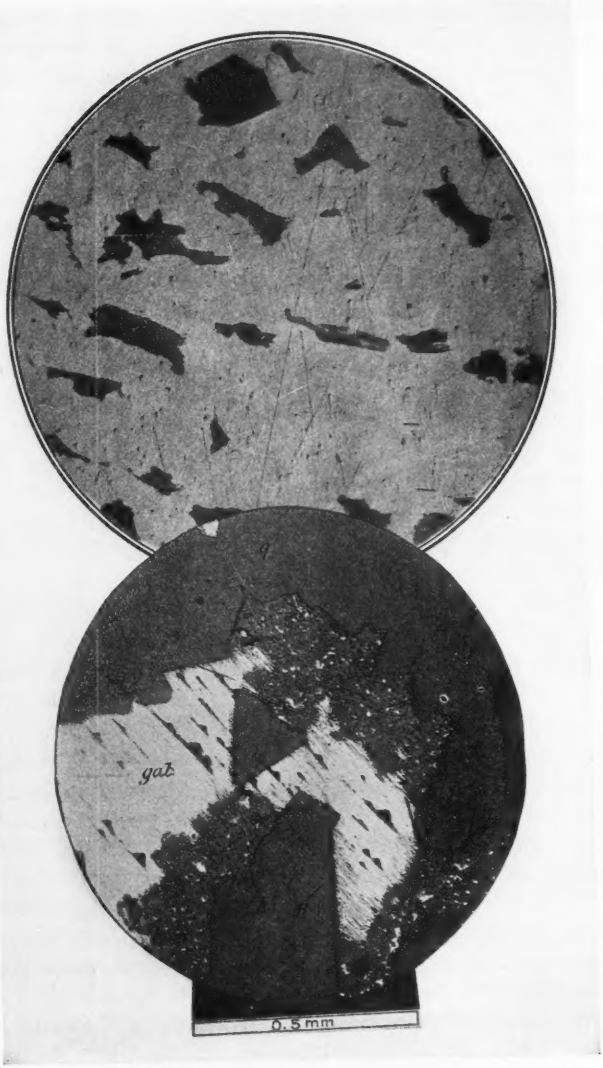
Conceivably isolated areas of *A*, parallelly oriented and surrounded by *B*, might be due to simultaneous deposition of *A* and *B* as in eutectic intergrowths or to deposition of *B* in open spaces on an irregular surface of *A*. When the isolation is due to replacement, other indications of such an origin may be present, such as definite veinlets, geological or geochemical incompatability, great variability from place to place in the ratio of guest to host, and sometimes ragged boundaries.

Form of the Host-guest Contact.—Where other evidences of replacement are present the form assumed by the contacts between guest and host minerals often affords confirmatory evidence.

FIG. 21 (Upper). Covellite (dark) in a field of chalcocite (light). Butte, Montana. × 158. (Bastin.) Note that the covellite usually shows concave boundaries as if it had been "bitten into" by the chalcocite. Such boundaries though not conclusive evidence of replacement frequently result therefrom and have been termed "caries" by Lindgren. (Compare Fig. 16.) Relations in other parts of this specimen show conclusively that chalcocite has replaced covellite.

FIG. 22 (Lower). Relatively coarsely crystalline galena (*gal*) and quartz (*q*) associated with a fine-grained aggregate of carbonate, electrum, argentite and chalcopyrite. Tonopah, Nevada. (Bastin.) The contacts of galena and quartz are crystal faces of quartz. This connotes nothing as to the relative ages of these two minerals. The great contrast in coarseness between quartz and galena and the aggregate of carbonate, electrum, argentite and chalcopyrite, and the absence of intermediate degrees of coarseness suggests that the two sets of minerals crystallized under different conditions and hence are diverse in age. The exceedingly ragged boundaries between the fine aggregate and the galena suggest that the aggregate has replaced the galena. "Islands" of galena off the "mainland" but with the same crystal orientation as the "mainland" confirm the replacement interpretation. The quartz in places (as at *A*) shows ragged outlines next the fine aggregate in marked contrast to its straight boundaries (as at *B*) next galena. This indicates that the fine aggregate has locally and to a minor degree replaced quartz.

That the replacing aggregate was deposited by hypogene rather than supergene solutions is suggested by its mineral composition—particularly the presence of electrum and chalcopyrite, which are not common supergene minerals.



FIGS. 21 and 22.

Depending on the structure of the host and probably also on the nature of the attack by the replacing solutions, the host-guest boundary may be either concave or convex towards the host.

Where the host has approximately non-directional qualities as far as attack by the replacing solutions is concerned, the guest seems usually to develop boundaries that are smoothly concave towards the guest, as if it had "bitten into" the host. For such embayments alternating with cusps, Lindgren has suggested the name *caries,* chosen from their similarity to dental caries. Such caries are common replacement phenomena and are illustrated in Figs. 16 and 21.

On the other hand, where strong directional qualities are apparent in the host, such as bedding, crystals diverse in composition and in orientation, or pronounced cleavage, the cusps, teeth or incipient veins of the guest project between the crystals or along cleavages of the host and the guest, and the boundaries are likely to be irregular, sometimes to the point of extreme raggedness (Fig. 20), and to lack the smoothly scalloped form of a succession of caries. Although caries are indicative of replacement, their absence does not imply an absence of replacement.

Finally it must be remembered that many guest minerals develop idiomorphic forms during replacement and thus present smooth and straight crystal outlines against the host (Figs. 11 and 12).

Contrasting Types of Replacement.

In replacement processes the replacing material may assume the form of the substance replaced (pseudomorphic replacement) or it may assume its own characteristic crystal form (idiomorphic replacement) or it may be deposited in a colloidal state ("gel" replacement) and assume the rounded contours common in colloids whatever may be their composition. A thorough discussion of these contrasting types and the physical laws controlling their deposition is beyond the scope of this report but certain points concerning them should be mentioned.

Pseudomorphic replacement, although commonly taking place in one step, may take place in two, as when woody tissue is re-

placed by silica to form "petrified wood" and this in turn is replaced by chalcocite with the perfect preservation of the cell walls.

Idiomorphic replacement is well illustrated by Figs. 11 and 12, which show perfect cubical crystals of pyrite transecting the schistosity of a fine-grained schist. Obviously the pyrite has developed by the simultaneous replacement of the several minerals of the schist. A further implication not generally recognized is that the several minerals of the schist must have been replaced at essentially the same *rate*, a somewhat astonishing fact in view of the diverse solubilities of these several minerals under most circumstances.

"Gel" replacement finds a familiar example in the development of rounded cherts in limestones. It consists of replacement by colloidal material deposited at first as a gel but later solidifying and usually crystallizing. Lindgren was apparently the first to recognize the importance of "gel" replacement in ore deposition.

Finally, it should be noted that the same mineral may under different circumstances be deposited in each of the ways indicated above. For example, pyrite in some instances replaces woody tissues (Fig. 10) or shells, with the perfect preservation of the organic forms. Elsewhere, as shown in Fig. 12, it assumes its own crystal form in replacement. In rarer instances it assumes in replacement rounded outlines suggesting that it was originally deposited in the "gel" or colloidal state.

As a comparatively new concept, gel replacement deserves somewhat fuller consideration. In open spaces gels are deposited commonly in reniform masses showing concentric bandings. Commonly they crystallize after deposition to cryptocrystalline, fibrous, or even coarsely granular aggregates. Silica may be so formed. If before consolidation, the gel is penetrated by electrolytes, precipitation may occur along recurring lines following the colloform texture. Such rhythmic precipitation of crystalloids in gels is known as Liesegang's rings.

A gel may also replace a rock resulting in cryptocrystalline, fibrous or microcrystalline material in which the original depositional colloform texture may remain. Before crystallization,

such gel masses are easily crushed and deformed. The colloform texture produced by replacement in solid rocks is not a familiar conception, but it certainly occurs. Flint nodules in limestone constitute the most familiar example of replacement of this sort. Similarly psilomelane may replace various rocks in the zone of oxidation. During this gel replacement colloform texture may develop, as well as in open cavities, and in replacement deposits a colloform texture is *prima facie* evidence of gel deposition.

Gel sulphides may replace gangue minerals or other sulphides. This is particularly the case in marcasite. Colloform texture develops in the marcasite. Rapid crystallization may produce shrinkage cracks, commonly filled with later carbonates. Colloform marcasite replaces quartz, pyrite, pyrrhotite, and sphalerite. Colloform sphalerite has also been observed as a replacement product.[24]

Special Features Bearing upon Replacement.

Residuals.—The ultimate results of long continued replacement of a granular aggregate are residual masses in a mass of replacing mineral. These residuals may be wholly irregular and jagged, because influenced by cracks and other planes, but commonly they are rounded. Such rounded residuals are shown by pyrite replaced by chalcopyrite or chalcocite.

Inclusions.—Irregular inclusions of one mineral in another rarely prove definite succession. They may be residuals after replacement, or they may be metasomes cut in such a way by the section as to cut off the duct or path of the replacing solution.

Mutual Boundaries.—Several kinds of minerals may border against each other by curved faces, from which no safe conclusion may be drawn as to mutual age relations. Such boundaries have been called mutual boundaries and have been thought to indicate simultaneous deposition. A case often observed is an intergrowth of pyrite, bornite, chalcopyrite and galena, all four exhibiting mutual boundaries. Examination of other parts of the

[24] For literature, see W. H. Newhouse, Paragenesis of Marcasite, ECON. GEOL., vol. 20, pp. 154–166, 1925.

ore will, however, usually disclose age differences. Newhouse has shown that in a clear case of age difference—as limonite after pyrite—the minerals are separated by such mutual boundaries.[25] Mutual boundaries do not therefore constitute a safe criterion of contemporaneity.

Notable Disparity in Size among Component Mineral Species.—The presence of certain minerals in prevailingly and notably larger or smaller grains than others is in certain instances suggestive of age diversity. The greater the disparity in size, the greater in general is its value as a criterion of age diversity. The criterion rests on the *a priori* postulate that under constant environmental conditions a group of minerals crystallizing out of solution tend towards moderate uniformity in size of grain. Notable departure from such uniformity on the part of certain minerals would, therefore, imply changed conditions and hence age diversity. There are of course many noteworthy exceptions to this rule as, for example, pegmatites, and the criterion must be applied with caution; it is not without value, however. The usual interpretation of phenocrysts of porphyries as differing in age from their matrix is a familiar example of the application of this criterion.

The fine-grained aggregate of carbonate, argentite, and chalcopyrite associated with relatively coarse galena and quartz that is shown in Fig. 22 affords an example of the applicability of this criterion in an ore showing replacement.

Graphic Intergrowths.—A number of observers, notably Whitehead, Rogers, Guild, Lindgren[26] and Schwartz have interpreted some at least of the graphic intergrowths found in ores as replacement phenomena, and as evidence of such replacement of a host mineral H by a guest mineral G, have cited, (a), boundaries that are serrate under high magnification and from which tongues of G project into H; (b), veinlets of G traversing H; (c), transitions from the intergrowths of G and H into unquestioned

[25] W. H. Newhouse, in Fairbanks, "Laboratory Investigation of Ores," 1928, p. 159.

[26] Lindgren, W.: Pseudo-Eutectic Textures. ECON. GEOL., vol. 25, pp. 1–13, 1913. (References to earlier papers.)

peripheral replacements of *H* by *G*; (*d*), caries of *G* in *H* at the borders of the intergrowths. Eutectic-like intergrowths of the following minerals have been observed: Bornite—Chalcocite (Laney); Bornite—Chalcopyrite (Van der Veen); Bornite—Galena (Short, Schwartz); Bornite—Stromeyerite (Guild); Galena—Stromeyerite (Guild, Schwartz); Galena—Argentite (Schwartz); Galena—Covellite (Schwartz); Galena—Tennantite (Lindgren); Galena—Proustite (Guild); Tennantite—Chalcopyrite (imperfect); Tennantite—Stromeyerite (Lindgren); Sphalerite—Chalcopyrite (Lindgren); Tetradymite—Altaite (Thomson).

According to Lindgren,[27] pseudo-eutectic textures usually result from the replacement of one soft mineral by another, the replacement proceeding irregularly and essentially uninfluenced by cleavage, fissures or other structures of the host. The process appears to be mainly a product of hypogene mineralization.

Rogers[28] and Graton[29] have both suggested that certain eutectic-like intergrowths may be a product of selective replacement of one component of a primary intergrowth. Undoubted replacement remnants of the older mineral would be the only convincing proof of such an origin.

More recently Schwartz[30] has described graphic intergrowths of galena and stromeyerite in which covellite has in places partially and elsewhere completely replaced the stromeyerite. In other specimens from the same locality the galena has been replaced by cerussite, although remnants of galena remain. The net result is a graphic intergrowth of cerussite and covellite which is a replacement of an original graphic intergrowth of galena and stromeyerite.

[27] Personal communication.

[28] Rogers, A. F.: The So-Called Eutectic-like Intergrowths of Bornite and Chalcocite, ECON. GEOL., vol. 11, p. 593, 1916.

[29] Personal communication, 1929.

[30] Schwartz, G. M.: Pseudo-eutectic Textures. Discussion. ECON. GEOL., vol. 25, pp. 658–663, 1930.

Criteria for Distinguishing Hypogene from Supergene Replacement.

After it has been determined by the use of the criteria already indicated that certain minerals have been deposited by replacement, it is important to determine whether the replacement has been accomplished by solutions of deep-seated or hypogene origin, or by solutions of surficial or supergene origin. At the outset it may be stated that in certain instances the problem of hypogene *vs.* supergene origin cannot at present be solved.

The criteria that have thus far been used are few, and their validity under certain circumstances is confessedly open to some question.

Composition of the Replacing Minerals.—Perhaps the most available criterion is based upon our knowledge of the geological and geochemical conditions under which various minerals are formed. This knowledge rests mainly upon field observation and subordinately on laboratory experimentation. It is known, for example, that certain minerals form only under the near-surface conditions of the oxidized zone. Replacements involving these minerals may safely be interpreted therefore as supergene. Common examples of such supergene replacements are replacements of galena by anglesite or cerussite, the replacement of chalcocite by brochanthite, and most replacements by cuprite.

On the other hand, it is equally well known that certain associations of lime silicates such as garnet, epidote, and wollastonite, that develop as replacements of limestones, form only under intense conditions of hypogene mineralization. In certain of the rich ores of Tonopah, Nevada, electrum occurs as a replacement mineral (Fig. 22). It is believed to be hypogene because under the conditions of the zone of oxidation silver and gold tend to part company and as a consequence if they are redeposited from descending solutions they are deposited, not in alloy with each other, but as separate minerals such, for example, as fine gold and argentite.

Unfortunately, there are a large number of minerals which it is well known can form under either hypogene or supergene con-

ditions and these include many minerals, such as native silver, silver sulphide and probably the sulphosalts of silver, whose origin it is often of great practical importance to diagnose.

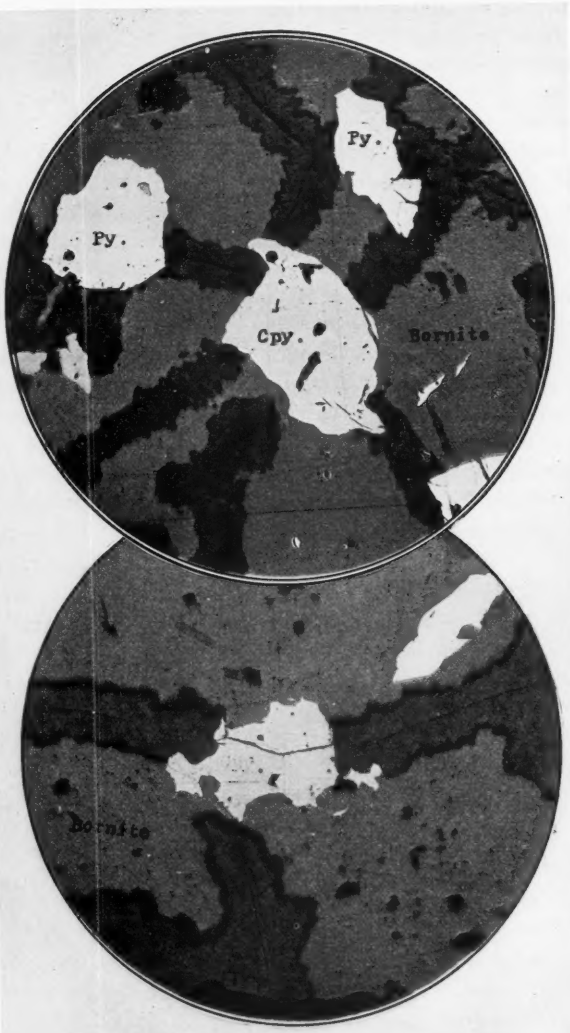
Replacement by One Mineral vs. Mineral Aggregates.—In the supergene replacements of the zones of oxidation and of downward enrichment it is rare to find two minerals simultaneously replacing the same host; commonly the replacement is by a single mineral only. If several minerals are deposited by supergene replacement, they are usually in sequence such, for example, as the commonly observed replacement sequence where galena is bordered by replacement rims of argentite and the latter by native silver. In short, supergene replacements, if involving several replacing minerals, are usually sequential and not aggregate replacements. Instances of simultaneous supergene replacement by *two* minerals have, however, been described.

Supergene replacements are also apt to be markedly selective (Figs. 23 and 24).

In hypogene mineralization, on the other hand, apparently simultaneous replacement of one or more host minerals by an aggregate of several guest minerals is common. Certainly the several minerals of the replacing aggregate show no clear evidences of age diversity. On a small scale an excellent example is afforded by the ore from Tonopah, Nevada, shown in Fig. 22.

FIGS. 23 AND 24. Veinlets of feathery covellite—dark gray (bordered by narrow rims of limonite)—developed in bornite (light gray) but not in pyrite (*Py*) or chalcopyrite (*Cpy*). Right Bower Mine, Butte, Montana, just below oxidized zone. ×96. The failure of opposite walls of the covellite veinlets to "match" and the presence in them of a central "parting" shows that they have been formed by replacement proceeding outward from narrow fractures in the bornite and are not fissure fillings.

The failure of the covellite veinlets to traverse pyrite and chalcopyrite indicates either (*a*) that the pyritic minerals were formed after the veinlets by replacement of both bornite and covellite, or (*b*) that the pyritic minerals were much less susceptible to replacement by covellite than was the bornite. The persistence of the central "partings" of some covellite veinlets across pyrite or chalcopyrite grains as shown in Fig. 24 shows the correctness of the second interpretation. These figures constitute, therefore, a striking example of selective replacement.



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It must not be inferred that sequences may not develop in hypogene replacement but they appear much less characteristic than in supergene replacement.

Depth Relationships.—Finally, depth relationships are suggestive though seldom conclusive criteria of hypogene vs. supergene replacement. If replacements on an important scale are found at depths well below the effective circulation of meteoric waters, the presumption is in favor of hypogene origin. At Tonapah, Nevada, replacements that on mineralogical grounds were interpreted as hypogene were found to persist without diminution in abundance to depths of 1250 feet, a fact which tended to confirm this interpretation.

On the other hand, the limiting in certain districts of some kinds of replacements to very moderate depths is indicative of supergene origin. At Aspen, Colorado, for example, replacement of argentite and some other silver minerals by native silver is common near the surface, but declines in depth and has not been noted below 1200 feet. The frequent limitation of chalcocite to depths of a few hundred feet is another example.

THE GENESIS OF THE LEAD–ZINC DEPOSITS AT PINE POINT, GREAT SLAVE LAKE.[1]

J. MACKINTOSH BELL.

CONTENTS.

Introduction 611
General Geology and Topography 611
The Presqu'ile Dolomite 614
The Ore bodies 617
Genesis of the Deposits 620

INTRODUCTION.

THE lead-zinc deposits to be described in this paper are situated near Pine Point on the southwestern shore of Great Slave Lake about 30 miles southwest of Fort Resolution, the most important trading post in that part of the Mackenzie River district (Fig. 1). Though the latitude in which the deposits occur is about 61° N., the climate is less severe than in similar latitudes on the eastern part of the North American Continent. The long winters with almost continuous heavy frost but relatively scant snowfall and the hot dry summers have probably influenced recent geological events as they affect the deposits to-day.

GENERAL GEOLOGY.

The Eastern part of the basin of Great Slave Lake, east of the delta of the Slave River, is occupied by pre-Cambrian rocks, the western part by Paleozoic strata. The pre-Cambrian area has so far not been examined in detail, but it is already clear that several series, sedimentary and igneous, are separated by pronounced unconformities, and that intrusives of various ages are widely dis-

[1] Presented before the Society of Economic Geologists, Toronto Meeting, Dec. 30, 1930.

tributed.[2] The boundary between the pre-Cambrian and the Paleozoic, masked by overburden, is thought to be about 40 miles west of the lead-zinc deposits.

The Paleozoic rocks immediately overlying the pre-Cambrian

FIG. 1. Regional plan showing Great Slave Lake.

are believed to be in part Ordovician and in part Silurian.[3] Above, is a series of Middle and Upper Devonian strata, divisible as follows:[4]

Middle Devonian
(1) *Pine Point Formation.* Soft gray shaly limestone, blue to black, thin-bedded hard limestone and gray to brown shaly limestone.
(2) *Presqu'ile Formation.* Crystalline cavernous dolomite, and thin-bedded, in places sandy, dolomitic limestone.
(3) *Slave Point Formation.* Gray shaly limestone.

[2] Lausen, Carl, "A Geological Reconnaissance of the East end of Great Slave Lake," *Can. Min. & Met. Bull.*, Feb., 1929; Bell, J. Mackintosh, "Great Slave Lake," *Trans. Royal Soc. of Can.*, vol. 23, Sect. IV, May, 1929.

[3] Hume, G. S., "Ordovician and Silurian Fossils from Great Slave Lake," *Geol. Surv. Can.*, Bull. No. 94.

[4] Cameron, A. E., "Hay and Buffalo Rivers, Great Slave Lake and Adjacent Country," *Geol. Surv. Can.*, 1921, Part B.

Upper Devonian
(4) *Simpson Formation.* Greenish gray shales weathering to fissile shales.
(5) *Hay River Lower Formation.* Shaly limestone and soft clay shale with limestone, sandstone, and ironstone bands.
(6) *Hay River Upper Formation.* Hard dolomitic limestone, shaly limestone and calcareous shale.

The Paleozoic rocks in the vicinity of Great Slave Lake have a general westerly or southwesterly dip, forming a great monoclinal fold or possibly the easterly limb of a geosyncline. The strata are gently folded in a direction parallel to the line of strike. Roughly at right angles to this general folding, or with axes trending approximately east and west, are less definite transverse folds. In many places small local domes appear. Although the inclination of the Paleozoic beds is for the most part so gradual that the rocks seem generally to be practically horizontal, dips up to 10° have been observed. West of Great Slave Lake, nearer the Rocky Mountains, where the Paleozoic rocks were more closely involved in the uplift of that chain, they are much folded and dislocated.

The Cretaceous and Tertiary rocks occurring at various places in the Mackenzie Basin have not been found in the vicinity of the lead-zinc deposits.

No igneous rocks are known to cut the Devonian rocks at Great Slave Lake itself, but "a dyke of altered andesite" is reported[5] to intersect Devonian shales on the Liard River about 280 miles west of the lead-zinc deposits and it is therefore possible that they may exist nearer the mineralization.

All the older rocks of the region are overlain by Quaternary material, consisting of glacial deposits and river and lake deposits. In the vicinity of the lead-zinc occurrences, material of this character shrouds most of the country. Its thickness, however, does not appear ordinarily to exceed, in that locality, 15 or 20 feet, and is commonly less.

Physigraphically considered, the pre-Cambrian rocks of the

[5] Jewitt, J. W., of the Consolidated Mining & Smelting Company, personal communication to the writer.

eastern part of Great Slave Lake form part of the Laurentian peneplain, which in this region is tilted towards the west. As a result, the extent of topographic relief diminishes from east to west. Local elevations of 1000 feet occur at the far eastern end of the lake, but near the Paleozoic boundary the old rocks rise only a few feet above the level of the water. The eastern part of Great Slave Lake itself shows the indented shore lines, the winding channels, the numerous islands; and the contiguous interior, the numerous lakes, so characteristic of Laurentian scenery.

The topography of the western part of Great Slave Lake is characterized by low and generally regular shore-lines, and by the absence of impressive relief inland. In the vicinity of the lead-zinc deposits the land rises gradually inland to a height of approximately 200 feet at about 9 miles from the shore. Very low ridges of sand or boulders are common inland, and nearer the existing strand, marshy stretches separate old lake beaches, trending generally parallel to the present shore.

THE PRESQU'ILE DOLOMITE.

All the lead-zinc mineralization so far found occurs in the Presqu'ile dolomite formation. Consequently it is desirable to describe this formation in some detail.

On the southwestern shore of Great Slave Lake the formation underlies a large section of country between the Little Buffalo and the Big Buffalo Rivers. As a result of the folding previously described, as well as on account of topographic irregularities, the formation is not continuous and areas of it are separated by stretches of the preceding and succeeding formations.

The thickness of the Presqu'ile dolomite on the north shore of Great Slave Lake is given as 375 feet.[6] On the south shore, the maximum thickness is not known. In many places where the formation is exposed near the principal lead-zinc deposits it is clear that large portions of it have been removed by erosion. Many churn drill holes have been sunk in the vicinity of certain of the deposits, but most of these are shallow—100 to 150 feet—

[6] Cameron, A. E., *op. cit.*

and have not penetrated to the underlying Pine Point rocks. The deepest hole had not reached the bottom of the formation at a depth of 255 feet. To the north and west, prospect holes have shown a lesser thickness in one or two places. To the southwest of the more important deposits, the bottom of the formation may be expected to be found progressively deeper in successive shallow synclinal folds until it passes entirely below the overlying Slave Point formation. So far there has been no drilling in that direction.

The Presqu'ile dolomite formation, as previously indicated, consists of crystalline cavernous dolomite and thin-bedded, in places sandy, dolomitic limestone. The surface exposures near the lead-zinc deposits are of the cavernous type, but the prospect shafts and churn drill holes in that vicinity penetrate the thin-bedded material. The latter apparently occurs in narrow layers throughout the formation but is more conspicuous towards the bottom and top, where it is fossiliferous. Argillaceous lenses are in places associated with it.

From an economic standpoint, interest naturally centers around the cavernous dolomite, which may be white, entirely recrystallized, and with open spaces surrounded by typical curved crystals of dolomite, or grayish and scarcely recrystallized at all. There is every gradation between these two opposing types, and a mottled gray and white rock, in places with wavy bands of the two colors, is common. In some of the deeper test-pits, somewhat removed from the center of mineralization, brownish crystalline dolomite occurs, the color and smell being due to small quantities of bitumen. In one locality about four miles to the north of the more important mineral deposits, irregular chunks of solid bitumen, probably albertite, have been found in open cavities in highly cavernous dolomite associated with dolomite and calcite crystals.

Since rich mineralization is limited to the porous dolomite, and occurs only in unimportant individual crystals or bunches of crystals in the thin-bedded dolomitic-limestone, the question arises as to whether dolomitization has any relationship with the mineralization other than the fact that it produced a cavernous rock through

which the mineral-bearing solutions could readily penetrate and in which the sulphides could be deposited. In this connection it is interesting to quote from A. E. Cameron[7] in regard to the oil pools in dolomites at Nintsi Point on the north shore of Great Slave Lake.

> A possible explanation of the oil seepages at Nintsi Point is worthy of notice. The sulphur-bearing waters rising from below carrying considerable quantities of calcium and magnesian salts and percolating through the over-lying thin-bedded dolomitic limestones change them to crystalline magnesian limestones and dolomites. In the process bitumen is set free and forced into the cavities in the dolomites, or through the fissures developed during dolomitization, to the surface, to form the tar and oil pools.

He goes on to say:

> Certain parts of the beds are not yet completely changed to dolomite but are made up of a coarsely crystalline white dolomite mixed with a more finely crystallized, dark brown, bituminous dolomitic limestone. No distinct line of separation exists between the two phases and there is a gradation of one into the other.

The fact which D. F. Hewett[8] points out, that "in a few regions the record [regarding regional relations of sulphide ore bodies and dolomite] indicates that no ore bodies are found without an envelope of dolomitized limestone or dolomite (Mississippi Valley) or in extensive masses of dolomitized limestone (Upper Silesia)", suggests a genetic connection between the dolomitization and mineralization, but the further fact which the same writer adds that in other regions similar deposits are enclosed in unaltered limestone, emphasizes the need for avoiding generalization.

In the region under review, the absence of numerous rock analyses from widely separated localities, and the lack of detailed geological investigation, prevent the expression of a definite opinion on this subject. As far as the relationship of the cavernous dolomite to the thin-bedded dolomitic limestone, or to the shaly limestone of the overlying and underlying formations, is known, one inclines to the opinion that the dolomite represents, at

[7] *Ibid.*

[8] "Dolomitization and Ore Deposition," ECON. GEOL., vol. 23, pp. 821–863, 1928.

least in considerable part, original marine deposition or alteration beneath the sea prior to uplift, but also is due in part to the ramification of solutions subsequent to uplift. The widespread distribution of the dolomite suggests the former, the irregular boundaries between the completely dolomitized rock and the less dolomitized or undolomitized indicates the latter.

THE ORE BODIES.

Although small deposits of lead and zinc minerals have been found at intervals over an area about 15 miles from east to west and 10 miles from north to south in the vicinity of Pine Point, the only important deposits so far located, those of Northern Lead Zinc Limited, occur within a rectangle about one mile long by about half a mile wide (Fig. 2). Here, there are five surface

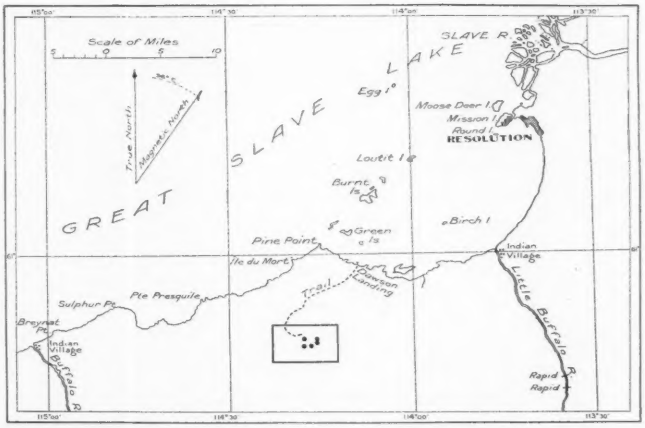


FIG. 2. Pine Point area showing position of lead-zinc deposits. Rectangle indicates general area held by Northern Lead-Zinc, Ltd.

showings. These were originally thought to be distinct—three roughly circular in shape and about 250 feet in diameter, a fourth more elliptical, 900 feet long by 200 feet wide, and a fifth considerably smaller, about 125 feet by 80 feet. Close churn-drilling

on two of the five deposits has demonstrated that ore occurs to a greater depth than originally supposed, that beds of low mineralization may separate successive beds of ore, that the deposits are extremely irregular in shape, and that ore is not limited to the surface croppings. Although it is clear from the work already done that there are many ramifying branches, it is not yet certain that all the deposits are connected, though such is quite possibly the case.

Certain surface features occur associated with the deposits and aid in exploration where the mineralization is not actually exposed. The most conspicuous of these are sink holes, and oxidation at the edges of dolomite outcrops. What are described as structural depressions,[9] that is, depressions which, on account of the shattered nature of the underlying dolomite, permit free drainage and consequently contain more vigorous vegetation than some other valleys, may also have a relationship to the occurrence of the deposits.

Where the ore outcrops, the vegetation is scant, the soil is rusty, reddish, brownish, or grayish, depending on the predominating sulphide, and there is commonly a considerable amount of ore detritus mixed with dolomite fragments. The ore appears to occupy zones of intensive jointing that may occur along minor anticlinal crests or domes. The general structure of the dolomite area in which the five deposits are found, however, appears to be that of a broad synclinorium.

The mineralization occurs in favorable dolomite beds, decreasing or increasing laterally; in vertical or inclined masses of highly irregular shape; in closely spaced small lenses in crumbly dolomite; and as a sort of breccia of dolomite fragments cemented by ore minerals. The strength of the mineralization seems to be greatest along lines parallel to the principal joint planes, and to weaken outward therefrom in impregnations of favorable beds. Thinly stratified beds of non-porous, sandy or argillaceous dolomite, are unmineralized or contain only occasional crystals of the sulphides. The deposits are oxidized in places down to a depth of 100 feet. Highly oxidized beds are found below those that show no obvious

[9] See also Siebenthal, C. E., "Origin of the Zinc and Lead Deposits of the Joplin Region," *U. S. Geol. Surv.*, Bull. 606, pp. 15, 183–184, 1916.

alteration. Open caverns, surrounded by gossanous material, are commonly encountered in drilling or test-pitting, and explain the sink holes that characterize the vicinity of the deposits.

Mineralogy.—The ore minerals of the deposits consist of galena, sphalerite, pyrite and certain of their oxidation products, more particularly cerussite (in small amount), smithsonite and limonite. The non-metallic gangue material consists of dolomite, calcite, and quartz—the last—named in minor quantity. The galena is, in places, coarsely crystalline with characteristic cubical cleavage, again it is fine-grained and intimately associated with sphalerite in similar form. The sphalerite is commonly botryoidal; the pyrite is generally finely crystalline.

Metallographic examination of the ores by J. Ellis Thomson,[10] has shown that the metallic minerals are of four ages, and that these are associated with three generations of gangue material, an earlier and later carbonate and a still later quartz. He gives the paragenesis as follows: (1) pyrite and first carbonate, (2) sphalerite, (3) galena and sphalerite, (4) second carbonate, (5) quartz, (6) alteration products. Pyrite and the first carbonate (probably mostly dolomite) appear to be nearly if not quite contemporaneous in deposition, and are both replaced by sphalerite and galena. Most of the sphalerite antedates the galena, but undoubtedly some of the sphalerite was still being deposited at a later period when the galena had started to crystallize and may even be later than some of the galena. The second carbonate replaces all these metallic minerals, and represents a distinctly later stage of mineral deposition. This stage was followed by the deposition of the later quartz and the development of such alteration products as limonite, cerussite and smithsonite. Thomson considers that the sequence of mineralogical events might be summarized as follows:

1. Deposition of first carbonate and of pyrite.
2. Period of movement, causing fracturing of these earlier minerals.
3. Deposition of earlier sphalerite replacing, in part, the earlier carbonate and the pyrite.
4. Deposition of galena and continued deposition of sphalerite.
5. Second period of movement producing openings along cleavage planes

[10] Thomson, J. Ellis, Communication to Northern Lead Zinc, Ltd.

and crystal boundaries in the metallic minerals and the earlier carbonate.

6. Deposition of the second carbonate in the openings mentioned under (5).
7. Third period of movement, less pronounced than the first two, producing openings in minerals formed at earlier stages.
8. Deposition of quartz and of metallic alteration products in the openings previously made.

Two drill-hole records given below illustrate the nature of typical ore in two distinct localities:

I Feet.		Assays. Lead %.	Zinc %.
0 –	8	8.27	4.44
8	14	24.86	14.96
14	20	Sample lost.	
20	25	23.41	24.53
25	30	31.11	21.49
30	35	15.98	13.75
35	40	25.38	9.74
40	45	21.91	11.31
45	50	7.71	13.78
50	55	9.59	10.44
55	60	2.63	2.96
60	65	1.79	.61
65	70	5.81	2.96
70	75	1.69	.70
75	80	1.03	.44
80	85	1.06	Tr.
90	95	Tr.	"
95	105	"	"

II Feet.		Assays. Lead %.	Zinc %.
0 –	5*	10.40	8.40
5	10	28.90	5.90
10	15	32.20	9.70
15	20	14.70	25.00
20	25	14.10	23.50
25	30	9.50	27.00
30	35	8.25	25.00
35	40	9.40	22.50
40	45	5.10	12.90
45	50	.20	6.10
50	55	.20	2.90
55	70	Tr.	4.10
70	75	.80	8.40
75	80	.70	9.20
80	85	5.90	15.50
85	90	2.60	9.00
90	95	.20	6.80
95	100	Nil	6.70
100	105	.20	3.60
105	110	Nil	4.70
110	115	.20	3.60
115	120	Tr.	Tr.

* Overburden and oxidation.

GENESIS OF THE DEPOSITS.

In the sediments laid down by the Paleozoic ocean that stretched from the Gulf of Mexico to the Arctic Ocean, sulphide ore bodies with many features in common have a wide geographical distribution. The principal metallic elements contained are lead, zinc, or iron. The deposits are not generally in the form of veins but more commonly occur in irregular ramifying impregnations that occupy porous beds or shattered and jointed zones. Although single deposits or groups of deposits may have considerable hori-

zontal range, they do not continue to great depths. They are, in some instances, definitely to be connected with faults or shattered zones; closely associated igneous rocks for the most part appear to be lacking.

In the Mississippi Valley there are many ore fields, the general geological conditions of which are not unlike those of Pine Point. The structural conditions of the latter appear to resemble closely those of Flat River, though there is much more zinc in the Great Slave Lake locality and nickel and cobalt have so far not been found there. There are, again, many similarities between Pine Point and the extensive mineralized district continuing through other parts of Missouri, into Kansas and Oklahoma (the Tri-State field), between it and the field of Northern Arkansas, and between it and the Upper Mississippi Valley district of southwestern Wisconsin, northwestern Illinois, and northeastern Iowa. Needless to say, there are features that differentiate the Pine Point locality from each of those mentioned, to which there is no space to allude in this paper. It is noteworthy that the chert found at Joplin and in other districts, has not been observed at Great Slave Lake.

Quite apart from the ore deposits of the Mississippi Valley of which the Mackenzie Valley of Canada, containing the Pine Point deposits, may be regarded as a northerly extension, lead-zinc occurrences that closely resemble those of Pine Point are found in many other parts of the world, in Upper Silesia, in the Vielle Montagne-Moresnet district and elsewhere.

As regards the various localities in the Mississippi Valley, a wide diversity of viewpoint has existed regarding the origin of the deposits. W. H. Emmons [11] summarizes the more important opinions into three hypotheses:

1. It is held that the deposits have formed by the agency of ground water descending or moving laterally through the rocks, and depositing the ores at the places they now occupy. This hypothesis, in one form or another, is supported by the investigations of Whitney, Chamberlin, Keyes, Black, Winslow, Buckley, Buehler, Grant, Cox, and Miser. Bain supports this theory to account for the Wisconsin zinc deposits, but not for the Joplin, Missouri, deposits.

[11] Emmons, W. H., "Sulphide Ores of the Mississippi Valley," ECON. GEOL., vol. 24, No. 3, p. 222, May, 1929.

2. A second hypothesis states that the ores are derived from rocks below those in which they are found; that the metals were leached by ground water from the deeper-seated rocks that rose as an artesian circulation to deposit the ores at the places in which they are now found. This theory is supported by Bain, Van Hise, Siebenthal, and Smith and Ball. Bastin has suggested that the precipitation has taken place through the agency of anaerobic bacteria.

3. A third hypothesis, that the ores were formed by thermal waters ascending from deep sources, was advocated by Jenney, Nason, Pirsson, Tarr, and Spurr.

F. L. Ransome, in his preface to Siebenthal's contribution to the subject in 1915,[12] says: "There can be no doubt that Mr. Siebenthal's careful observation and cogent reasoning have gone far to establish on a firm foundation the general conclusion that ordinary cold artesian water may under some circumstances be a very efficient agent in the solution, transportation, and deposition of the constituents of certain sulphide ores." Siebenthal[13] summarizes his viewpoint in the same publication in this sentence: "These waters [deep waters] are therefore probably the agents of dolomitization and siliceous replacement, as well as of mineralization." He emphasizes, further, the point that there are no deposits of ore where overlying impervious shales are unbroken.

In a previous contribution[14] the writer, after indicating that in the pre-Cambrian region to the eastward of Pine Point there were numerous small veins carrying pyrite, galena, and sphalerite, points out that:

1. It is possible that these are the remnants of more extensive deposits of similar character, the weathering outcrops of which fed the Paleozoic seas with lead, zinc and iron salts to be widely distributed as sulphide (or other salt) in the sediments then being deposited, and that later, after uplift, these sulphides (or other salts) were dissolved by ramifying meteoric waters, from which they were reprecipitated in the presence of bituminous material to form appreciable concentrations.

2. It is also conceivable that the iron, zinc and lead salts dissolved by

[12] Siebenthal, C. E., "Origin of the Zinc and Lead Deposits of the Joplin Region," *U. S. Geol. Surv.*, Bull. 606.

[13] *Ibid.*, p. 8.

[14] Bell, J. Mackintosh, "The Lead and Zinc Deposits near Pine Point, Great Slave Lake," *Trans. Can. Inst. Min & Met.*, 1929.

surface waters from the veins of the pre-Cambrian highlands to the eastward were carried down the westerly dip of the Paleozoic beds, and that the solutions rose under artesian conditions along lines of structural weakness to deposit their metallic burden in the presence of a favorable precipitant.

In other words, in the light of insufficient geological data available at the time the paper quoted above was written, he felt unprepared to discard either of the first two of the three hypotheses given by Emmons, nor yet to accept the third, or theory of hydrothermal origin, which Emmons himself favors in connection with the sulphide ores of the Mississippi Valley. Recent information, however, seems to have clarified the viewpoint, and to suggest the probability of the association of the deposits, possibly remotely, with igneous activity.

Although the rocks in the vicinity of the deposits are almost flat-lying, they are far from being undisturbed; there is widespread if gentle folding, probably major and certainly minor faulting, and such widespread and intricate jointing as to suggest greater movement than that for which there is actual evidence. It is conceivable that tectonic disturbances may have influenced the widespread dolomitization, or at any rate initiated the dolomitic recrystallization so closely connected with mineralization.

The fact that there is in places a faint suggestion of zoning of the deposits of the three elements lead, zinc and iron, not only as regards an individual deposit but as regards a group of deposits, agrees better with a thermal origin than with either of the conceptions tracing their genesis to the agencies of ground water.

In regard to the origin of the sulphides, as a result of an examination of polished ore sections, Thomson has this to say:

Considering the metallic mineralization in general as shown by the specimens examined, particularly the presence of considerable iron-poor sphalerite, also the presence of small quantities of a sericitic mica, and the general carbonate-like character of the gangue material, it seems probable that this metallic mineralization was effected through the agency of some deeply-buried igneous source, the ore-solutions of which operated at moderate depths, penetrating, through the available openings, to great distances from the original magmatic source.

No igneous rocks later than the Middle Devonian are known to exist anywhere near the lead-zinc deposits, but in a region where so very little bed rock is exposed, west of the pre-Cambrian, this, needless to say, does not mean they do not exist. As far as the pre-Cambrian area is concerned, it is quite possible that intrusive rocks as recent as late Devonian do occur there, indistinguishable petrologically from much older intrusives, and inseparable therefrom because of the absence of later sedimentary rocks, from which their age could be judged. The Caribou Mountains, the northerly slope of which rises about 60 miles to the south of the deposits to a height of about 2000 feet above them, are practically unknown. Such information as is available suggests that they are composed of sedimentary rocks, and are either a Cretaceous outlier, or uplifted block or blocks similar to many other elevated areas to the east of the Rocky Mountain uplift.

The nearest post-Devonian intrusive so far reported is that indicated by Jewitt, as cutting Upper Devonian shales on the Liard River, about 280 miles west of Pine Point. It may be mentioned, by the way, that this narrow andesite dike has directly associated with it a small lens of quartz and chalcopyrite, with a little galena.

In addition to the formation of oxides of iron and carbonates of lead and zinc, the results of metallographic investigation, quite apart from field evidence, suggest the formation of secondary sphalerite in the process of oxidation. Definite recognition of sulphide enrichment in the field is difficult, but this hypothesis, when the differential solubility of the sulphides is remembered, explains, it is believed, the fact that the shallower deposits appear to be generally richer in lead than the deeper. The writer believes that the hydrothermal theory of origin of the primary mineralization at Pine Point harmonizes more readily with the information so far available than does either of the other hypotheses, and whatever the origin, he feels that since their original deposition, there has been elemental migration during the process of alteration, which has substantially enriched the deposits in places.

ALMONTE, ONTARIO.

CHROMITE DEPOSITS NEAR SHERIDAN, MONTANA.[1]

VERNER JONES.

WHILE making a reconnaissance near Sheridan, Madison County, Montana, the writer noted some deposits of chromite ore, whose lithologic relations are so unusual as to seem worth recording.

As is well known, chromite deposits are commonly found associated with, or enclosed in, rocks derived from a very basic magma, such as dunite (Kenai Peninsula, Alaska),[2] peridotite (North Carolina),[3] a serpentinized olivine, enstatite rock (Southern Rhodesia),[4] pyroxenites with segregations of saxonite (Singhbhum, India),[5] talc schist and silicified serpentine (Southern Rhodesia),[6] pyroxenite (Stillwater and Sweetgrass counties, Montana),[7] and olivine-gabbro (Cuba).[8]

The deposits here described form lenticular masses or segregations in a series of diorite dikes, located on the western slope of the Tobacco Root Mountains, 3 miles south and 4 miles east of Sheridan, near the eastern border of the Dillon quadrangle. They are not to be confused with the well known chromite belt in Stillwater and Sweetgrass counties over 100 miles to the east.[9]

GENERAL GEOLOGY.

The country rock of the ore is a gneiss which is a portion of

[1] Presented before the Society of Economic Geologists, Toronto meeting, Dec., 1930.

[2] Gill, A. C., U. S. Geol. Surv. Bull. 742, 1922.

[3] Lewis, J. V., *Eng. and Min. Jour.*, vol. 109, pp. 1112–1114, 1920.

[4] Keep, F. E., South. Rhod. Geol. Surv. Bull. 16, p. 22, 1930.

[5] Mahadevan, C., ECON. GEOL., vol. 24, p. 195, 1929.

[6] Maufe, H. B., Lightfoot, B., and Zealley, A. E. V., South. Rhod. Geol. Surv. Bull. 3, p. 89.

[7] Westgate, L. G., U. S. Geol. Surv. Bull. 725 A, pp. 67–84, 1922.

[8] Burchard, E. F., *Trans. Amer. Inst. Min. and Met. Eng.*, vol. 63, p. 160, 1920.

[9] Westgate, *op. cit.*

the rock mass mapped by Peale [10] as Archean in the neighboring Three Forks quadrangle.

Cutting the gneiss is a series of diorite dikes that strike northeast and dip 40 to 60 degrees west. These dikes attain a width of two hundred feet or more and can be traced for at least a mile along the strike. No mention of this diorite is made by Winchell [11] in his description of the Sheridan Mining District, nor has it been referred to by Peale [12] or Merrill [13] in that portion of the Three Forks Quadrangle immediately adjoining this area. However, a diorite was mapped and described by them along the northern boundary of the Three Forks Quadrangle, about 45 miles from the chromite area. In neither of these reports is chromite mentioned.

Numerous irregular quartz veins, and in one case a hornblende-hypersthenite, cut the gneiss near the diorite dikes, but their exact relations were not determined. A hornblende-hypersthenite has been described by Merrill [14] from the Three Forks Quadrangle about twelve miles to the east where it is said to outcrop in a general circular form approximately 100 feet in diameter, cutting the gneiss. It is not improbable that further work may reveal some genetic relationship between the hypersthenite, and the chromite-bearing diorite.

The diorite is of two types: (1) A coarse-grained dark-colored rock which makes up the main diorite dikes and within which the chromite bodies are found; (2) a fine-grained nearly black diorite, which was observed at only one point and does not exceed two feet in width, forming a segregation within a dike of coarse-grained diorite. It assays .47 per cent. Cr_2O_3.

The chromite, so far as could be determined, occurs as lenses in the coarse diorite, which show a maximum observed thickness of 5 feet. It is massive, with an indistinct banded structure, and contains occasional streaks of talc.

[10] Peale, A. C., U. S. Geol. Surv. Folio 24.
[11] Winchell, A. N., U. S. Geol. Surv. Bull. 574, pp. 132–139.
[12] *Op. cit.*
[13] Merrill, G. P., Proc. U. S. Nat. Mus., vol. 17, p. 656, 1894.
[14] *Op. cit.*

PETROGRAPHY.

Gneiss.—This is usually a light-colored banded rock but grades into darker shades with the development of hornblende and garnet. The epidote, in many cases, is a conspicuous constituent, in places giving the rock a greenish tinge. In thin section, the rock shows 30 to 50 per cent. quartz with from 5 to 20 per cent. oligoclase as primary minerals. Hornblende is present in anhedral grains, associated with and including small grains of magnetite. Sericite, carbonate, and garnet were observed in notable quantities but the most prominent of the secondary minerals is epidote, which in one case makes up nearly 40 per cent. of the section.

Diorite.—Under the microscope the coarse-grained diorite shows andesine and hornblende (Fig. 1) as essential minerals, with apatite, quartz, pyroxene, and magnetite as accessory ones. Sericite, chlorite, garnet, and epidote occur as alteration products.

The fine-grained diorite is composed of andesine and hornblende with minor amounts of augite. Biotite, hornblende, magnetite, and possibly phlogopite occur as alteration products. Most of the crystals are so small as to make the rock appear quite fine-grained, the hornblende being largest and often twinned, as well as showing reaction rims of biotite and secondary hornblende. The plagioclase is much finer grained and in some cases shows a zonal arrangement with the more acidic bands on the outside.

Hornblende-hypersthenite.—Megascopically this is a dark, nearly black rock of fine-grained texture showing a large number of small glistening rod-like crystals of hornblende and hypersthene. The surface shows some white and rusty weathering products. Thin sections show hypersthene and hornblende making up most of the rock. Minor amounts of magnetite, pleonaste and possibly chromite are present. The pleonaste and magnetite, or chromite (?), usually occur together (with the opaque mineral as a core of the pleonaste) or they may occur alone. In most cases they are associated with the hornblende as inclusions or in contact with the hypersthene, but rarely included in it.

Chromite.—Thin sections of the ore show subhedral to

rounded anhedral chromite grains, mostly intergrown with amphiboles (probably pargasite) and minor amounts of phlogopite (Fig. 2). In some cases there are small tongue-like extensions of chromite penetrating the silicates suggesting that some of the ore mineral, at least, may be of late magmatic age.

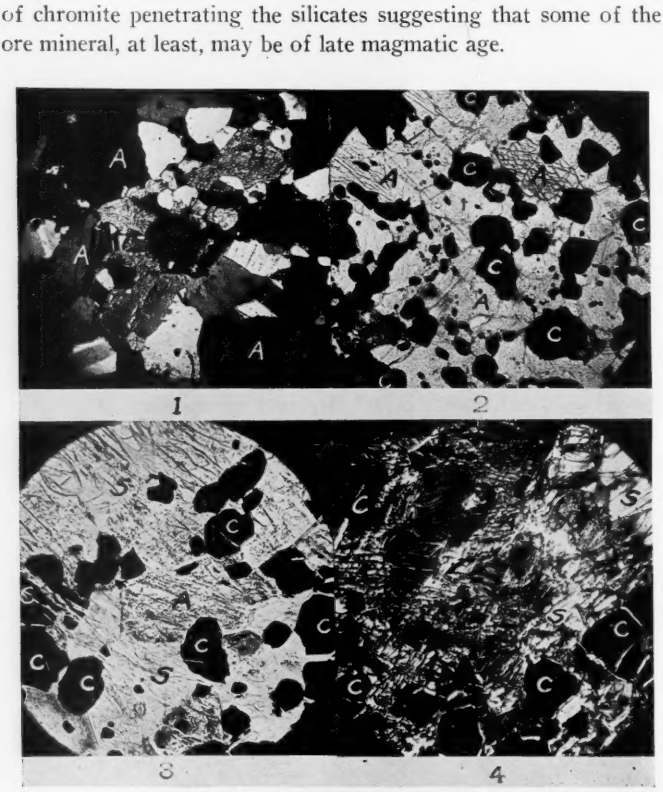


FIG. 1. Coarse-grained diorite. Hornblende (H); andesine (A). X-nicols, × 30.

FIG. 2. Chromite (C) and gangue of amphibole (A). Ordinary light, × 40.

FIG. 3. Chromite (C) with gangue of serpentine (S); traces of amphibole cleavage (A). Ordinary light, × 40.

FIG. 4. Chromite (C) in gangue of serpentine (S); showing amphibole cleavage partially retained (A). X-nicols, × 30.

Some sections show only chromite, serpentine (Fig. 3), and scales of phlogopite. The origin of this serpentine has caused some speculation, but the writer is inclined to believe that most of it has been derived from the amphibole for the reason that the prismatic cleavage of the latter is, in some cases clearly preserved (Figs. 3 and 4). It is possible also that a little of it is an alteration product of the phlogopite, because in some cases it can be clearly seen replacing the latter mineral. There is no olivine present in the fresh rock. That there has been some migration of the serpentine is shown by the fact that it fills cracks cutting across chromite grains (Fig. 3).

Origin.—The relationship of the chromite to the enclosing diorite together with the presence of amphibole as the predominant gangue mineral, indicate that the chromite represents a segregation in diorite. If this is the case, it shows a lithologic relationship which is different from any deposit that the writer has seen mentioned in the literature.

Mining Operations.—Owing to the fact that only a few prospect pits have been opened up in the ore, a detailed study of its geologic relationships is somewhat difficult. The ore is not high grade since it assays only 21 to 35 per cent. Cr_2O_3.

Acknowledgment should be made to Messrs. John McNair of Coolidge, Montana, and Angus C. Reid of Butte, Montana, who made it possible for the writer to visit the property.

CORNELL UNIVERSITY,
ITHACA, N. Y.

GOLD IN CADILLAC, QUEBEC.*

L. V. BELL.

CONTENTS.

INTRODUCTION 630
TOPOGRAPHY 632
GENERAL GEOLOGY 632
Detailed Geology of the Principal Mineralized Zone 635
GOLD MINERALIZATION 636
CHARACTER OF THE DEPOSITS 637
RELATION OF THE DEPOSITS TO ROCK STRUCTURES 639
INFLUENCE OF COUNTRY ROCK ON MINERAL DEPOSITION 640
Wall Rock-Alteration 641
ORIGIN OF THE DEPOSITS 642
GOLD PRODUCTION 643

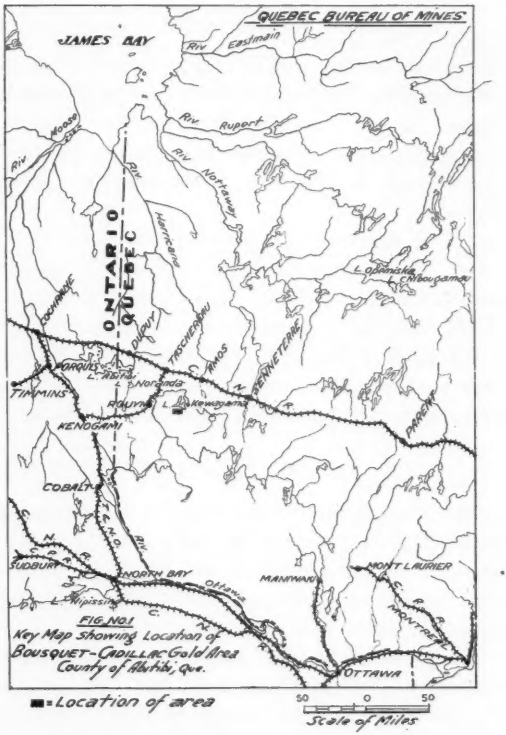
INTRODUCTION.

WHAT has been termed the Bousquet-Cadillac area is situated in the townships of those names in the Abitibi district of Quebec. The principal mineralized area which is discussed in the subsequent pages constitutes, however, only a small portion of the two townships, and forms a narrow belt extending in an easterly direction from northeastern Bousquet to north-central Cadillac townships. Several mining properties are situated along this belt or zone, the principal of which are: O'Brien, Pandora, Thompson-Cadillac, and Graham-Bousquet.

This small mining district lies approximately 23 miles south and 15 miles west of Amos, a town located on the Quebec-Cochrane branch of the Canadian National Railway (Fig. 1). The district is also about 25 miles due east of the towns of Rouyn and Noranda. It lies within a belt of predominantly sedimentary rocks which have been classed as Timiskamian, and are believed to represent the easterly continuation of the Timiskamian strata that are well known in the Kirkland Lake field.

* Presented before the Society of Economic Geologists, Toronto meeting, December, 1930.

The following account of the deposits of the district is more or less a summary of the results obtained during two field seasons that were spent in the general vicinity for the Quebec Bureau of Mines. An examination of the gold deposits was commenced in


QUEBEC BUREAU OF MINES
JAMES BAY
Riv Eastmain
Riv Rupert
Riv Nottaway
Moose
Riv
Riv Harricana
ONTARIO
QUEBEC
Riv Ogoki
Riv Abitibi
Riv Mattagami
L. Abitibi
L. Timiskaming
L. Nipissing
L. Temagami
L. Obonga
L. Shebandowan
L. Nipigon
L. Superior
L. Michigan
L. Huron
L. Erie
L. Ontario
Riv Ottawa
Riv St. Lawrence
Riv Mississippi
Riv Missouri
Riv Columbia
Riv Yukon
Riv Mackenzie
Riv Saskatchewan
Riv Red
Riv Winnipeg
Riv Nelson
Riv Churchill
Riv Athabaska
Riv Peace
Riv Fraser
Riv Thompson
Riv Skeena
Riv Stikine
Riv Liard
Riv Pelly
Riv Yukon
Riv Porcupine
Riv Hudson
Riv Connecticut
Riv Hudson
Riv Delaware
Riv Susquehanna
Riv Potomac
Riv Rappahannock
Riv James
Riv Roanoke
Riv Tennessee
Riv Ohio
Riv Kanawha
Riv Kentucky
Riv Wabash
Riv Illinois
Riv Missouri
Riv Arkansas
Riv Red
Riv Rio Grande
Riv Colorado
Riv Gila
Riv Sacramento
Riv San Joaquin
Riv Columbia
Riv Snake
Riv Yellowstone
Riv Platte
Riv Kansas

to Messrs. Dufresne and Dresser, of the Quebec Bureau of Mines, for making possible the presentation of this paper. For a further discussion of the district, the reader is referred to the Annual Report of the Quebec Bureau of Mines for 1929 (Part C).

TOPOGRAPHY.

The Bousquet-Cadillac mining region lies, for the most part, west of the height of land, and forms a part of the drainage basin of the Ottawa River. East of the height of land, which traverses Cadillac township in a northeasterly direction, the waters flow northward through the Harricana River and connecting lakes into James Bay.

The relief of the area is nowhere pronounced. Low ridges, usually with some outcropping strata, provide a contrast to the much more extensive low-lying areas covered with glacial drift. Much of this low, flat ground forms swamps or muskegs, particularly during wet seasons. The ridges and valleys have a definite east-west trend which corresponds to and is controlled by the structural trend of the underlying rock formations.

GENERAL GEOLOGY.

The solid rocks throughout the area are of pre-Cambrian age. These are extensively overlain by deposits of Glacial and post-Glacial time, so that exposures of the underlying rock are relatively rare. In Table I. the rocks are classified according to their relative ages, the oldest being at the bottom.

Table I. is a modified form of that given for the area by James and Mawdsley.[1] The areal geology has been systematically mapped by the officers of the Geological Survey of Canada and this has greatly facilitated the present more detailed examination of the deposits.

The following brief description of the regional geology applies to an area 40 miles in a north-south direction by 30 miles in an east-west direction, and including 12 townships.

The principal mineralized zone herein described is located in

[1] Geol. Surv. Canada, Summ. Rept., 1924, Pt. C; 1925, Pt. C.

TABLE I.

TABLE OF FORMATIONS.

Quaternary.

Recent and Pleistocene—Lake clays, sand, gravel, till.

Great Unconformity.

Pre-Cambrian.

Pre-Cobalt (?) possibly Keweenawan—Later olivine gabbro, quartz gabbro.

Intrusive contact

Pre-Cobalt (Algoman)—Granite, diorite, syenite, and syenite porphyry.
Quartz monzoniite.
Amphibolite.
Lamprophyre.
Older gabbro and peridotite.

Intrusive contact.

Timiskaming—Greywacke, arkose, conglomerate, and altered equivalents.
Basic flows, tuffs, agglomerates, and altered equivalents.

Unconformity.

Keewatin—Volcanics: basalt, andesite, rhyolite, and tuffs; basic intrusives of doubtful affinity.
Sediments: conglomerate, arkose, argillite.

the west central part of the area outlined. The northern part of the area is underlain essentially by Keewatin volcanics and in part by granitic rocks intrusive into them. The granitic rocks become much more extensive in the northeastern part of the region. The southern, in strong contrast to the northern part of the area, is underlain essentially by fine-grained sedimentary rocks of the Timiskamian, the major portion of which may be termed greywacke. Minor bands of volcanic rock occur within this predominantly sedimentary series, to which they appear to correspond in age. These Timiskamian rocks are intruded on the south by a large batholith of granitic rock similar in character to that lying to the north within the Keewatin volcanics. The chief mineralized zone is confined almost exclusively to one of the relatively narrow bands of volcanic rock that occurs within the northern part of the sedimentary series (Timiskaming) and hence

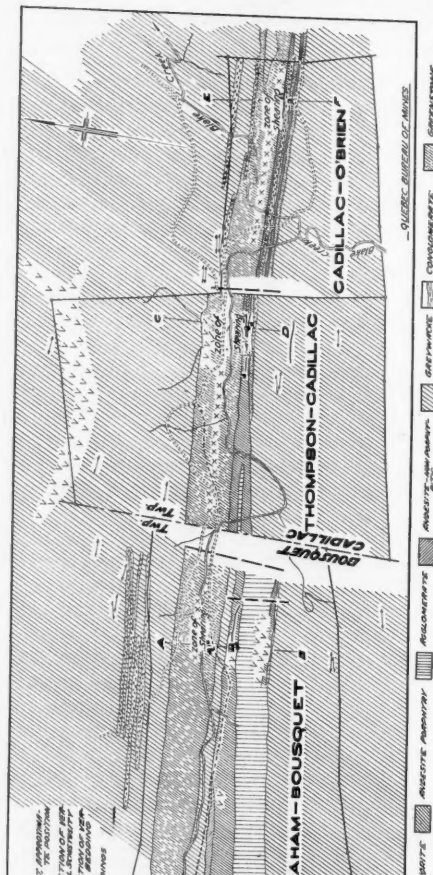


FIG. 2. Map of central part of the Bousquet-Cadillac gold area, County of Abitibi, Quebec, Canada.

near the major contact with the Keewatin. It is thus seen that the rock in association with the deposits is essentially of Timiskamian age.

Detailed Geology of the Principal Mineralized Zone.—The distribution of the several types of rock forming the principal zone, and those in the near vicinity, is shown in Fig. 2. As already pointed out, rocks of volcanic origin are much more closely related to the deposits than are the more widespread sedimentary beds forming the country rock to the narrow zone of volcanics. The several types of volcanic rock making up this zone may be classified as "greenstone," andesite (porphyritic and non-porphyritic phases), agglomerate, and tuffaceous rocks.

For the most part these different rock types form rather narrow, but regular bands with a constant east-west strike. It is worthy of note that by far the greater part of the important mineralization is confined to the two relatively narrow bands of porphyritic andesite. Although the several types which together make up the zone of volcanic rocks could well be grouped under the general term "greenstone," it is used here in a special sense for those rocks that are so altered as to render their original nature a matter of conjecture. The major band of "greenstone" is largely composed of chloritized and talcose schist, and forms the locus of a zone of faulting and shearing that has given rise to this altered type of rock. The zone appears to extend, with varying intensity of shearing, throughout the length of that portion of the mineralized zone mapped in detail, and to be very closely related to it from a genetic standpoint.

Intrusive rocks occur only in minor volume within, and in the vicinity of the main zone. These are of three types. The most widespread is a somewhat altered diorite that intrudes both the rock of the volcanic belt and the associated sediments; less well represented is a massive, fresh-looking aplite, intrusions of which are almost completely localized to the zone of shearing within the band of "greenstone"; a few outcrops of "later" gabbro occur where these narrow but persistent northeasterly trending dikes intersect the main zone. Of these three types of intrusives, only

the aplite appears to be connected with the mineralization. There is some evidence that the diorite has preceded the period of mineralization; the age of the later gabbro relative to the period of mineralization is an open question. The writer favors the theory, but for no very well-founded reason, that the gabbro was intruded later than the period of mineralization. Dr. H. C. Cooke[2] has established the fact that the "later" gabbro of Dufay township, Quebec, is older than the Cobalt series. This would indicate that the "later" gabbro of western Quebec is not of the same age as the Nipissing or Keweenawan diabase of Ontario.

GOLD MINERALIZATION.

The deposits described in this paper form a part of what appears to be a more or less continuous mineralized zone which, from west to east, extends from the Granada mine in Rouyn, to the Pandora mine in Cadillac township. This zone has a length of 35 miles and is characterized throughout by the same type of mineralization. It lies within the belt of Timiskaming sediments, but is more or less localized to the Keewatin-Timiskaming contact. Ten miles southeast of the Pandora showings are the claims of the Malartic gold mine in Fournière township, and roughly intermediate between these two locations, in addition to some others, are the mineral occurrences formerly worked by the Lartic and Malrobic mines in Malartic township. Whether the mineralization of these three properties may be considered to represent a continuation of the main zone is not definitely known. It is a fact worth noting, however, that the mineralization occupies a similar horizon in the band of Timiskamian sediments. The fact that these occurrences are to the south of the projected location of the easterly-striking mineralized zone is accounted for by the corresponding southeasterly swing of the band of sediments on the east of the Pandora mine. It should be noted that the important mineralization of the Malartic mine differs somewhat from that typical of the Bousquet-Cadillac district.

[2] Personal communication.

CHARACTER OF THE DEPOSITS.

The portion of the mineralized area that is discussed in this paper has a length of approximately seven miles and exhibits a uniform type of mineralization throughout this distance; the deposits consist essentially of deep-seated quartz veins carrying metallic sulphides and gold. Two types of mineralization may, however, be recognized as forming a part of the general type. They are as follows: (1) Mineralized quartz veins and lenses; (2) mineralized zones consisting of a network of small quartz stringers.

Quartz Veins.—This type is the common and more important one and is typical of the deposits of the O'Brien, Pandora, and Thompson-Cadillac mines. The deposits of this class occur in steeply dipping quartz veins and lenses, the strike of which parallels the direction of schisting of the associated rocks. The veins are of the fissure type and are in general narrow. Several of the veins are, however, quite persistent, and show mineralization over considerable distances. Narrow lenses of quartz also occur parallel to the schist and more or less *en échelon.*

The gangue minerals consist essentially of quartz, with subordinate amounts of carbonate, feldspar, and tourmaline. The quartz is commonly dark and glossy, although white quartz also occurs with it to some extent, the latter being typically represented in the principal vein of the Pandora property. In thin section, the vein quartz shows a mosaic of quartz grains with rare occurrences of small nests made up of crystals of plagioclase feldspar. This would suggest that the veins are pegmatitic in origin and therefore deep-seated. Carbonates also occur to some extent, and appear to be contemporaneous with the quartz filling. Tourmaline may be present locally in some abundance, but is not on the whole a common constituent.

The metallic minerals consist essentially of the sulphides of iron. Arsenopyrite is common both in the wall rocks and in the quartz. Pyrrhotite is also relatively abundant, but seems to be more closely confined to the quartz. Although the pyrrhotite is mostly disseminated, it was noted in one occurrence in the O'Brien

mine as a band, three to four inches in width, paralleling the quartz of the No. 4, or high grade vein for some little distance. Pyrite occurs in general rather sparingly in proportion to the other two sulphides. Other metallics include gold, or chalcopyrite and galena. Galena has been noted only rarely in the O'Brien mine, where it most commonly occurs in the high-grade sections of No. 4 vein. It will be noted that the dominant mineralization consists of arsenopyrite and pyrrhotite, both of which are indicative of high temperature conditions.

Gold values appear to be more or less dependent upon the degree of silicification, or in other words, gold is in general found in the quartz, rather than in the altered mineralized rock bordering the veins. There is a tendency for the gold to occur in irregular, rather small, but high-grade shoots in the veins. This feature is particularly true of the deposits of the O'Brien mine. The gold is essentially free and may occur in spectacular visible form. In some such cases it occupies cross fractures in the quartz transverse to the strike of the vein, and thus resembles parallel metallic leaves or plates. Gold appears to have been connected with the last phase of metallic mineralization.

Mineralized Zones.—The mineralized zones, consisting of networks of quartz stringers, are exemplified in a single instance by the deposit of the Graham-Bousquet mine. The deposit appears to have been formed in an irregular fractured zone within schisted porphyritic andesite adjacent to its faulted contact with greywacke. The fault may have caused the fracturing of this zone, which attains a width of over 70 feet on the upper level of the mine. Filling the numerous irregular fractures are a series of little quartz stringers or veinlets that form a network. The rock adjacent to each of these quartz veinlets is bleached and altered to carbonate. Where such veinlets become numerous, as in the main body of the deposit, the entire rock mass is bleached to a light grayish color and altered to carbonate. The zone thus silicified and carbonated is moderately well mineralized, and with the exception of pyrite, which is relatively much more abundant, carries a similar assemblage of metallic minerals to that of the

veins already described. Visible gold is lacking, although the entire zone is auriferous. The deposit appears to be analogous to the gold-bearing carbonated bodies at Larder Lake which have been described by Brock,[3] Hopkins,[4] and others.

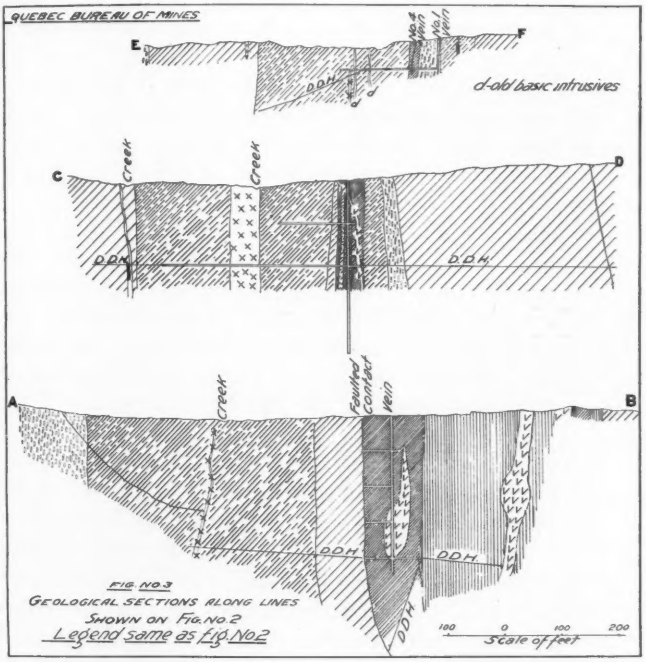


FIG. 3. Geological sections along lines shown on Fig. 2. Legend same as for Fig. 2. Diagonal black line on left of A–B is a diamond drill hole.

RELATION OF THE DEPOSITS TO ROCK STRUCTURES.

The form assumed by the deposits is controlled primarily by the structure of the enclosing rocks (Fig. 3). The tendency has been for narrow, tabular bodies of quartz to form parallel to the

[3] Ont. Bur. Mines, vol. 16, 1907, p. 207.
[4] Ont. Bur. Mines, vol. 28, 1919, p. 2.

planes of schisting. The general strike of the schisting is east-west and the dip is vertical, to which the veins and lenses correspond closely. In the bedded rocks the schistosity coincides essentially in direction with that of the bedding planes.

Although the veins are of the fissure type they do not appear to occupy fissures that represent any considerable fault-movement. The walls of the veins are usually fairly well defined and show pronounced schisting and shearing, which results in alteration of the wall rock, and frequently in slickensided surfaces. This seems to have resulted from pre-mineral faulting and fissuring, but only of a relatively minor nature, and, as already mentioned, corresponds closely to the regional schisting of the rocks.

There appears to be a definite relationship between the deposits and the zone of shearing and faulting, now represented by highly contorted, talcose schist. The foliated schist seems to represent a well-defined zone of weakness extending through the region. It is significant to note that the deposits of the various properties lying within the principal mineralized area are closely confined to this zone of intense shearing. The fact that the deposits occur outside of the zone rather than within it, is to be expected. The soft, foliated, and talcose nature of the rock would not have provided suitable channels for vein-forming solutions, nor is it probable that fractures would have been maintained in so plastic a rock. One would expect that any deposits that had formed within the zone would be very irregular, with little continuity, and probably lens-like in character. This is true of the rather rare mineral occurrences which have been noted within the zone. It is an interesting fact that the deposits of the four principal mining properties are in each case situated a short distance to the south of the principal zone of shearing.

INFLUENCE OF COUNTRY ROCK ON MINERAL DEPOSITION.

The deposits as a whole are confined essentially to the area underlain by several types of volcanic rock. This may be due to the proximity of the zone of weakness represented by intense shearing within the band of volcanics, or it may be due to dif-

ferences in the nature of the country rock. Of the several veins that occur, only one of importance lies within rock that is unquestionably of sedimentary origin. This is the No. 1 vein of the O'Brien mine, which occurs in a narrow band of conglomerate lying completely within the belt of volcanic rock. Several mineralized veins carrying some values are known to occur within the greywacke outside of the volcanic belt, but these are relatively of little importance. It would thus appear that volcanic rock has proved more favorable for mineral deposition than has sedimentary rock, particularly the fine-grained sediments.

The several deposits appear to be more or less confined to the harder phases of the volcanic rock, and more particularly to the porphyritic andesite. This is believed to be due to the hard physical nature of the rock, rather than to any difference in chemical composition which might have had an effect on mineral deposition. Such rock is hard and is thus competent to maintain any fractures that might have formed in it. It has already been pointed out that, by similar reasoning, the talc-chlorite schist was not favorable for mineral deposition. Whether the fact that the veins within the greywacke do not, in general, show much promise, is due to the physical nature of the rock, is not known. The explanation may lie in the fact that the greywacke beds are more remote from the zone of shearing than are the volcanic rocks. It should, however, be pointed out that the important gold mineralization of the Malartic mine occurs within greywacke that forms a part of the same principal belt of Timiskamian sediments.

Wall Rock-Alteration.—In common with many Canadian pre-Cambrian gold areas, the most typical form of wallrock alteration is that of carbonatization. There appear to have been two periods of carbonatization, an earlier period during which there has been rather extensive alteration to carbonate of the rocks associated with the deposits, and apparently a later period, confined essentially to the veins. Carbonate of the later period seems to have been introduced with the vein quartz.

Carbonatization of the rocks is usually indicated by the assumption of a light grayish color with alteration to rust on weathered

surfaces. Much of the rock is commonly so highly carbonatized as to react readily with dilute acids. This form of alteration is in particular extensive throughout the mineralized body of the Graham-Bousquet mine.

Chlorite, sericite, and sometimes talc, are commonly developed in the walls of the veins, and appear to have resulted in large part through shearing action.

ORIGIN OF THE DEPOSITS.

James and Mawdsley [5] have suggested two probable sources of origin for the ores of the region: (1) the southern granite batholith, the northern contact of which roughly parallels the mineralized zone; and (2) other intrusives following a line of weakness within the main zone. From observations made in that portion of the zone described in this paper, it would seem that the latter supposition is highly probable.

Lying within the intensely sheared volcanic rock ("greenstone") of the four principal mining properties, is a dike, and in some cases dikes, of light-colored, fine-grained aplite. These dikes thus occupy the main zone of weakness, and are clearly later than the period of shearing of the zone. The aplite is most likely a differentiate of the large masses of granite, the distribution of which has been briefly outlined. The only other intrusives within the near vicinity which would appear to have a probable genetic association with the deposits are the masses of diorite already described. These may also be differentiates of the granite, but are believed to be older than the aplite, and are quite probably older than the granite also. The diorite shows more extensive alteration than does the typically fresh-looking aplite. It seems probable that the quartz veins, most of which appear to have been pegmatitic in origin, would be associated with the more acid intrusive as a differentiate. The aplite consists essentially of soda feldspar and primary quartz, with practically no ferromagnesian constituents. Consequently, the only real difference in mineral composition between the aplite and the quartz veins is a

[5] Geol. Surv. of Canada, Summ. Rept. 1924, Pt. C, pp. 122–123.

preponderance of quartz in the latter with a corresponding deficiency in feldspar. It is thus inferred that the mineralized quartz veins have a genetic relationship with the aplite which is in turn a differentiate of the granite.

The mineral assemblage of the veins; arsenopyrite, pyrrhotite, pyrite, and tourmaline, is clearly indicative of high temperature conditions during the period of mineralization. A further indication of the high temperature and deep-seated nature of the deposits is provided in the fact that the veins are of pegmatitic origin. Mineralization seems to have taken place at great depth and at high temperature.

GOLD PRODUCTION

Production of gold in the region has to date been very small. Practically all the gold produced has come from the O'Brien mine, although a very small amount has been recovered by a pilot mill employed at the Thompson-Cadillac mine. Cobbing and shipping of the extremely high-grade portions of the ore with extraction of the gold in the mill at Cobalt has been the practice employed by the O'Brien company. Encouraging developments at the mine have resulted in the installation of a new mining plant. There is every likelihood that this will result in a greatly enhanced gold production in the near future.

BUREAU OF MINES,
QUEBEC, CANADA.

THE GEOLOGY OF THE SAN ANTONIO GOLD MINE, RICE LAKE, MANITOBA.

J. A. REID.

CONTENTS.

HISTORICAL NOTE 644
GENERAL FEATURES 644
LOCATION 644
TOPOGRAPHY 644
GENERAL GEOLOGY 645
LOCAL GEOLOGY 647
MINERALOGY 652
WORKINGS 653
VEINS 653
ORIGIN 657
SUMMARY 659

HISTORICAL NOTE.

IT was in the Rice Lake area east of Lake Winnipeg that the first discovery of gold was made in Manitoba, the find being on the Gabrielle claim in 1911. Subsequent operations on the Gabrielle, Moose, Gold Pan and other claims, however, achieved no tangible results. The original San Antonio group of three claims, the Ross Fraction, the San Antonio, and the Island Fraction, were among the earliest staked in the region, but until 1927 exploration was confined to surface work and sampling. On March 20th of that year, underground work started and continued until September 6, 1930, when the property was closed for refinancing.

GENERAL FEATURES.

Location.—The San Antonio Mine is on the north shore of Rice Lake (Fig. 1), about 30 miles from the east shore of Lake Winnipeg; it is 100 miles northeast of the city of Winnipeg.

Topography.—The Rice Lake area has the usual features of the Pre-Cambrian Shield of central and northern Canada, *i.e.* an

irregular hummocky surface, in part rocky and in part composed of glacial debris, interspersed with lakes and swamps. The bed rock formations are fairly well exposed on the more prominent ridges, and these trend northwesterly, the same as the strike of the underlying rocks. The difference of elevation in the district

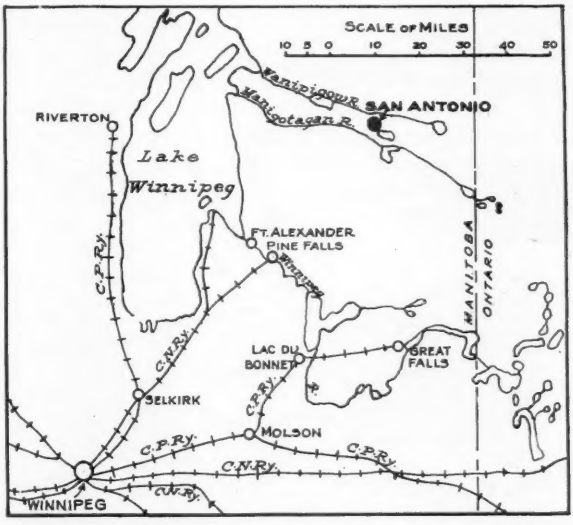


FIG. 1. Index map showing location of San Antonio Mine.

rarely exceeds 100 feet. One of the most prominent and continuous rocky ridges in the area lies along the north shore of Rice Lake immediately north of the San Antonio mine. The property, since it lies either in the lake or in the swampy area adjoining thereto, has but few outcrops and these consist of several knolls along the shore and islets in the lake (Fig. 2).

General Geology.—The Eastern Manitoba gold mining region is divided into two parts by a large granite stock, 11 to 12 miles long (east and west) by eight miles wide. The eastern part is known as the Long Lake area, and the western, the Rice Lake section; the latter consists of an irregular wedge-shaped area of

metamorphosed pre-Cambrian sedimentary and igneous rocks which are surrounded and intruded by granite and granite gneiss, also of pre-Cambrian age. The greatest width of the area, 9 to 10 miles, is at the east end, to the east of Rice Lake. It tapers westward, the west end being outside the mapped area, within

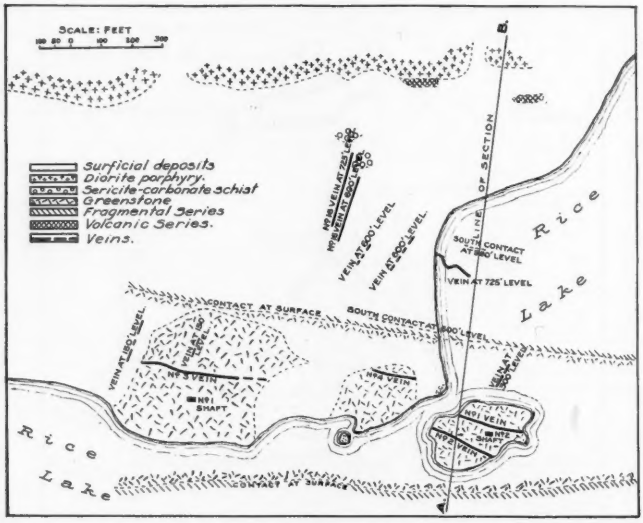


FIG. 2. Geologic plan of San Antonio Mine, Rice Lake, Manitoba.

which it has a length of 15–16 miles in a northwesterly direction.

According to J. F. Wright,[1] there is the following sequence of formations, the youngest being uppermost in the list:

Intrusives	
1. Fine grained porphyritic dikes	Granite, granodiorite, diorite.
2–3. Granite,[2] Granite--Gneiss	Including porphyritic and granodioritic phases.
4. Basic Intrusives	Peridotite, hornblende gabbro, diorite
Rice Lake Series	
5. Wanipigow Phase	Graywacke, chert, quartzite, arkose with conglomerate lenses.

[1] Map 195 A, Beresford and Rice Lake Area, Can. Geol. Surv., 1927.

[2] The diorite porphyry (3) shown on Figs. 2 and 3, on Map 195–A, is called a porphyritic phase of the granite.

6. Beresford Lake Phase	Trachyte, rhyolite, tuff, agglomerate; graywacke chert, iron formation, and carbonate rock.
7. Predominantly Volcanic Rocks	Andesite, trachyte, trachyte porphyry, and rhyolite with lenses of chert, tuff, and iron formation.
8. Manigotagan Phase (Highly metamorphosed)	Graywacke, slate, meta-argillite quartzite, in part altered to quartz-biotite and quartz-biotite-garnet schists, with granite and pegmatite.

The Rice Lake area as a whole is a large roof pendant imbedded in the granite. The above formations, except the massive granite, strike northwesterly and dip northeasterly or southwesterly parallel with the prevailing schistosity of the region. In the southwest part of the area, group 8 is nearly separated from the remainder of the series by a long tongue of granite. South of this tongue, the rocks generally dip southwesterly at angles of 75° to 80°; north of the tongue, they dip northeasterly. Around Rice Lake, which is near the center of the area, the dip is 45° to 60° and is steeper to the north and south of it.

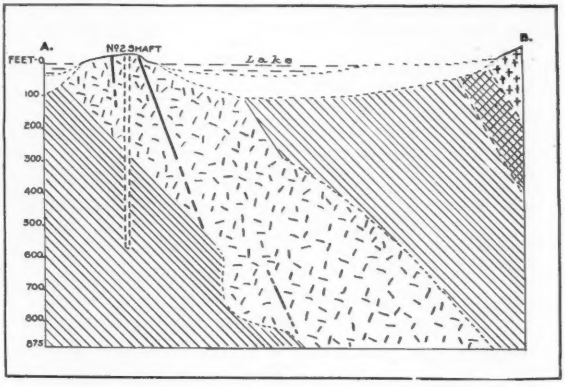


FIG. 3. Geologic section, San Antonio Mine.

LOCAL GEOLOGY.

The geology of the area adjoining the San Antonio mine is shown on Figs. 2 and 3. The following sequence of formations has been found, the youngest uppermost.

Diorite porphyry (intrusive)
Sericite—carbonate schist. (relationship undetermined)
Greenstone (intrusive)
Fragmental series (sedimentary and pyroclastic)
Volcanic series (extrusive)

Diorite Porphyry.—This rock outcrops on a ridge (70 to 80 feet high) along the northern shore of Rice Lake. It is a lenticular body, two miles long (E–W) by 2200 feet maximum width. The porphyry is slightly schistose throughout and markedly so around the borders. Its underground relations are as yet unknown.

In hand specimens the porphyry shows numerous white feldspar phenocrysts, 10 to 14 mm. long, in a fine-grained greenish-gray matrix; quartz is absent or infrequent. Under the microscope the rock is seen to be strongly altered. It has a seriate porphyritic fabric, the phenocrysts varying in size from 2 to 14 mm. The feldspar phenocrysts are altered to aggregates of sericite, zoisite, and some epidote, and clear secondary feldspar. The phenocrysts appear to have been plagioclase, midway between oligoclase and andesine. The ground mass is composed of secondary minerals, clear untwinned plagioclase, chlorite, epidote, zoisite, and carbonate; quartz is absent or rare in most of the sections. Ilmenite altered to leucoxene is infrequent. The porphyry is shown in Map 195 A. as a porphyritic phase of the regional granite. Although it may be an offshoot from the same magma, it is much more basic and is highly altered and, therefore, must be an early phase of that rock.

Sericite-Carbonate Schist.—This rock has only been found underground in the extreme northeasterly ends of the 600 and 725-foot levels. In detail, it has a ragged interfingering contact with the greenstone and in a larger way it appears to be a body of irregular shape, since it does not conform to the regular strike of the local rocks. In hand specimens the rock is a typical light gray to yellowish sericite schist. Under the microscope it is seen to be composed of sericite, quartz, carbonate (probably siderite), and residual cores of clear untwinned feldspar. It shows rather abundant nests of rutile crystals which appear to have resulted

from the progressive breakdown of ilmenite (ilmenite → leucoxene or titanite → rutile), and in one slide some titanite remains. Toward the sericite schist the greenstone shows a progressive increase in carbonization, reaching a maximum at the contact, beyond which, in the sericite schist, the carbonate decreases somewhat and sericite becomes the dominant mineral; the chlorite tends to become bleached and disappear, being replaced by sericite, and the leucoxene or titanite changes to aggregates of rutile crystals.

The sericite schist is a rock of doubtful origin; in many respects it resembles the schistose fragmental rocks that flank the greenstone on both sides; the latter rocks, however, contain andalusite, which has not been identified in the sericite schist. It differs likewise in the peculiarity of its field relations, and until further information is available it is assumed to be of igneous origin, representing either a hydrothermal alteration of the greenstone or a highly altered tongue from the porphyry to the northeast. As will be explained later it shows a distinct relationship with the distribution of gold in No. 16 vein.

Greenstone.—This rock is the most important one on the property, since the ore bodies are invariably found within it. It is covered by water and swamp over the greater part of its length, so that its size and relation to the other rocks are only known from a few scattered outcrops supplemented by underground work and diamond drilling. It is known, however, to be a dike-like body in schistose fragmental rocks extending completely across the property from northwest to southeast. From drill hole data it is 630 feet wide 250 feet northwest of No. 1 shaft, and 340 feet wide 1920 feet southeast of the same point.

In appearance the greenstone is a dark green, medium to fine-grained igneous rock. Near the veins it is quite schistose, but in other places rather massive; it has everywhere undergone metamorphism that masks its original character; in places, it shows traces of ophitic or diabasic texture. Under the microscope the rock is seen to be changed to aggregates of secondary minerals including chlorite, ferruginous carbonate, epidote (with the

closely allied mineral clinozoisite), sericite, and quartz. Sericite seems generally to characterize the more schistose parts of the rock, and epidote the more massive; in places it is essentially an aggregate of epidote and quartz. Ilmenite partly or wholly changed to leucoxene is abundant. The original texture shows in only one place.[3] A thin section discloses saussuritized plagioclase laths, from 3 to 10 mm. in length with ophitic relations with allotriomorphic individuals of partly chloritized secondary hornblende; epidote is rather plentiful but quartz, sericite and carbonate are absent. The rock has the present composition of a diorite, but as the hornblende is undoubtedly secondary, it was probably originally a rather coarse diabase or medium-grained gabbro.

Fragmental Series.—The greenstone is flanked on both sides by a series of fragmental rocks which on an island about 1000 feet southwest of No. 2 shaft show conglomeratic phases. Underground, these rocks are fine-grained and schistose; under the microscope they are seen to be composed of sericite, ferruginous carbonate, quartz, chlorite and some leucoxene or titanite (largely to rutile). All the thin sections show important quantities of a biaxial negative mineral, varying from colorless to pleochroic in faint yellow and reddish tints, with a refringence distinctly higher and a birefringence slightly lower than quartz, and with numerous inclusions that appear to be rutile. The extinction is parallel to the rarely observed cleavage. The mineral is extensively altered to micaceous and chloritic secondary products. It is most characteristically developed at the porphyry contact. It has the properties of andalusite.

These rocks both in hand specimens and under the microscope appear to be fragmental; the presence of andalusite and the decomposition products of ilmenite, the former a mineral resulting from the metamorphism of clayey rocks and the latter characteristic of igneous rocks, suggest that the original rocks were likely slates or greywackes in part, at least, of pyroclastic origin.

Volcanic Series.—According to Map 195 A., a band of volcanic rocks, 600 to 1000 feet wide, lies along the north shore of Rice

[3] On an island in Rice Lake about three-quarters of a mile southeast of No. 2 shaft.

Lake immediately south of the porphyry. It is not, however, in contact with the greenstone. The only place where this or a similar rock was observed on the San Antonio property is on the north shore of the lake adjoining the porphyry, 1050 feet northeast of No. 2 shaft; here there are several small outcrops of schistose basic igneous rock extending about 400 feet in a northwesterly direction. The rock is intensely sheared at the porphyry contact, the schistosity diminishing as distance is attained therefrom. In hand specimens the rock appears to be a typical chlorite schist. Under the microscope it is seen to be composed of chlorite, carbonate, secondary quartz, and untwinned sericitized feldspar; it is speckled with abundant ilmenite, which in the more schistose phases is wholly altered to rutile crystals. In the less altered phases, the rock appears to have a medium texture and the feldspar to be a basic oligoclase (about Ab 75 An 25). This rock has the composition of an altered andesite but is rather coarser grained than most extrusive rocks. The rock strongly resembles the more altered phases of the greenstone described above, but it is too far north to be part of that formation, and is therefore tentatively correlated with the volcanic series. It appears to wedge out to the west or northwest between the porphyry and the sediments.

Structure.—The strike of the formations, as mentioned above, is northwest and the dip to the northeast, varying from 45° at Rice Lake to 80° near the granite contact to the northeast. There are four systems of shearing or fracturing on the property, of which only the first has been observed outside of the greenstone; they are as follows: (1) The prevailing regional schistosity which is approximately coincident in strike and dip with the rocks in which it occurs; one of the two vein systems agrees with this in strike, but dips more steeply (65° to 70°) northeast. (2) A system with a northwest strike and a dip of 60° southwest; this occurs in two fractures on the surface which have never been found underground. (3) Fractures on shear zones striking northeast and dipping 30° to 68° northwest. This comprises the more important of the two mineralized systems of fracturing.

(4) A system striking nearly north and dipping west. One fracture of this kind was found in the 950 foot level; it is occupied by a barren quartz vein and it cuts and displaces No. 16 ore shoot on this level. Nos. 1 and 3 are considered to be two sets of contemporaneous intersecting cracks and to be older than the others. There appears, however, to be some reopening and slight subsequent movement along the northeast system, as it sensibly deflects veins belonging to the northwest series. No. 2 seems to be younger than No. 1 system but its relation to the others is not known. No. 4 is the latest, as it cuts No. 16 vein belonging to No. 3 system and has faulted it thirty feet to the east.

MINERALOGY.

Quartz.—There appear to be three generations of quartz: (1) White quartz (with accompanying coarse pyrite), which is barren or carries very low values; (2) a second generation, darker in color, which is associated with fine-grained auriferous pyrite; (3) white quartz with carbonate; this also is barren and occurs as flat stringers cutting the other two kinds mentioned.

Carbonate.—Iron-bearing carbonate is plentiful in the country rock adjoining the veins and not uncommonly replaces the greenstone, especially in the "stock work" veins where it forms a considerable part of the vein stuff; in the quartz veinlets themselves or veins belonging to the northeast system it is absent except where associated with quartz stringers of the third generation. Some of the carbonate in the wall rock appears to be siderite.

Feldspar.—The northwest veins on the surface show in places a reddish feldspar. No thin sections were made of this material, but it probably has the composition of albite.

Pyrite.—Pyrite of two generations is found in the deposits; the earlier occurs in cubes up to 5 mm. in size, and is found both in the veins and in the adjoining wall rock. This kind appears to be barren of gold. The later pyrite is fine-grained and cryptocrystalline with a brassy luster; it is associated with the darker second-generation quartz and it commonly occurs in bands or

streaks parallel to the vein walls. Gold is contained in or closely associated with this form of pyrite.

Chalcopyrite.—This mineral is found in the quartz but is of rather rare occurrence.

Gold.—With the exception of a vein recently found on the 950 foot level, visible gold is uncommon. It is characteristically associated with later pyrite in the second generation quartz. It rarely occurs as visible particles of small size in or adjoining the sulphides, or around dark spots in the quartz. Although little of it is visible, the gold appears to be mainly if not exclusively in the free state, since 80.5 per cent. of it is recoverable by amalgamation. In the exception above noted on the 950 foot level, the gold occurs as small visible particles in white quartz accompanied by scant sulphide mineralization.

WORKINGS.

The workings comprise two vertical shafts, No. 1 and No. 2, which are as yet unconnected. No. 1 shaft develops No. 3 vein on the north shore of the lake. It is 150 feet deep, with a level at this horizon. No. 2 shaft, on an island adjoining the north shore of the lake, is 930 feet southeast of No. 1. It is 600 feet deep with 125-foot, 300-foot, and 600-foot levels. Below the 600-foot level, an inclined winze extends to a depth of 950 feet with levels at 725 and 950 feet. The total amount of underground work is 11,500 linear feet.

VEINS.

The ore occurrences are confined to the greenstone body described above. Three types are known, the first strikes northwest and dips northeast, the second strikes northeast and dips northwest, the third also apparently strikes northeast with an undetermined dip. This third type resembles the first in structure and the second in strike but differs from both in character of mineralization.

The first type of veins strikes about parallel with the formations and the regional schistosity, and dips in the same direction but at

steeper angles, 64° to 68°. Consequently, these veins are successively cut out by the greenstone footwall, which dips 46° NE. Four major showings of this kind, Nos. 1, 2, 3, and 4, and several smaller ones, are known on the surface, and another was found underground. Nos. 1, 2, and 3 have been explored underground. The northwest veins consist of masses of quartz stringers and lenses with intermixed carbonatized greenstone and abundant pyrite, the whole forming stockworks of irregular shape and indefinite boundaries. Insufficient work has been done on these showings to determine their dimensions in every case, but two of them are about 300 feet long and in places up to 30 feet wide. The irregularity in the shape appears to be due in many cases to the intersection of the regional northwest shearing with northeast fissuring which has caused a deflection of the veins. Their central parts commonly show a succession of short quartz lenses 2 to 3 feet wide with an aureole of stringers in carbonatized greenstone, the stringers extending out into the relatively less altered wallrock for distances up to ten or fifteen feet, giving the widths stated. In some cases the central lenses are lacking and the lode consists of a mass of stringers in carbonatized greenstone gradually fading out into the walls. The sulphide mineralization is most intense about the central part and dies out towards the sides and ends. The better gold values occur in these central parts and are associated in all cases with seams of fine second-generation pyrite. However, as the same parts of the lodes contain the more conspicuous earlier pyrite, it commonly happens that a section which appears promising carries poor values in gold. In the northwest veins the distribution of the gold is in shoots; patches of good ore, 3 to 4 feet wide by 15 to 25 feet long, are surrounded and separated by longer sections of poor material. This appears to be due to the facts that the fine auriferous pyrite mineralization is confined to the central parts of the veins, and that it seems to be discontinuous and patchy and possibly connected with areas of northeast fissuring. There is, however, a continuous section of good ore on one of these veins on the 725-foot level, where for a length of 184 feet and a width of 3.7 feet, the vein averages $11.30

per ton. This part of the vein is quite crooked owing to repeated deflection by northeast fracturing; it shows more fine pyrite than any of the other veins of this class, and the seams of fine pyrite turn nearly at right angles following the deflections of the lode.

The second class of vein, of northeast strike, has not so far been found on the surface. The dip is northwest at angles varying from 30° to 68°. These veins tend to persist with depth and are not cut out by the footwall of the ore zone. The northeast veins occupy rather clearly defined shear zones and have a definite vein-like form. The quartz is strongly banded and carries much auriferous pyrite. Several of these veins have been found but only one (No. 16), has so far been developed, so a description of it will serve for the type.

The No. 16 vein occupies a shear or fracture zone 4 to 6 feet wide; above the 725-foot level it dips 68°; below, it flattens to 58°. It is laminated with alternate bands of white and dark quartz and some thin sheet-like remnants of schistified wallrock. The vein matter is strongly mineralized with both coarse and fine pyrite, (8–10 per cent. of total sulphides) but the latter is more conspicuous and occurs as streaks up to 2 inches wide parallel to the lamination (Fig. 4). The dark quartz appears to be later than the white and the fine pyritic streaks tend to follow or to be associated with it. Visible gold is rare, and where observed is either in or adjoining the sulphide streaks or dark spots in the quartz. Both kinds of quartz and the sulphide bands are cut by a third generation of flat stringers, 1 to 3 inches wide, consisting of white quartz with some carbonate; these stringers do not extend beyond the vein walls. Although banded, the veins show no drusy cavities, or the symmetrical banding characteristic of crustification. The individual bands of white and dark quartz are lenticular and pinch out along the strike, a white band being succeeded by a dark one, or vice versa. Barren stringers extend into the walls, particularly on the hanging wall side. On the 600-foot level at the southwest end, the shear zone is about 5 feet wide, with only 6 inches of well mineralized quartz; but northeast, this increases to an average width of 3.7 feet for 260 feet, with an

average gold content of $23.14. Beyond this the values cease, and the vein splits into stringers, passing into sericite-carbonate schist. The northeast half of the shoot is distinctly richer than the southwest half, the former averaging $28.88 over 3.6 feet

FIG. 4. Vein structure on No. 16 Vein at the 600-foot level. *a*, Barren 1st generation white quartz. *b*, Second generation dark quartz and fine auriferous pyrite. *c*, Barren 3d generation flat quartz and carbonate stringers. Width of vein about four feet.

and the latter $17.22 over 3.7 feet. At the center of the shoot a raise was put up on the vein for 108 feet; gold continues for 80 feet at which point the vein again splits and the values disappear. On the 725-foot level the shoot has the same dimensions and averages $16.66; here also, the northeast end is the richer, 74 feet running $22.78 over 3.0 feet, the remainder of the dis-

tance, 186 feet, averaging $14.86 over 4.0 feet. At the northeast end of the shoot, the vein frays into stringers and for 79 feet is only one foot wide, with good values, and terminates against sericite-carbonate schist. Four other northeast veins are known, two in the No. 1 shaft workings (150-foot level) and two in the No. 2 shaft workings (300- and 600-foot levels). Two of these veins carry good values over narrow widths. None of these veins have been explored into the favorable northeasterly area where they might intersect bodies of sericite schist.

The third type of vein has been found on the 950-foot level at the northeast end of the workings. It consists of a mass of quartz stringers 20 feet wide, showing considerable visible gold with little sulphide mineralization. The strike is apparently northeast, but as it was found just before the mine closed, nothing very definite is known about its size and value. In respect to the frequency of visible gold and comparative lack of sulphides it is different from the showings hitherto described.

ORIGIN.

In central Canada there is a well founded belief, born of experience, connecting gold deposits with bodies of intrusive porphyry; at the San Antonio mine, however, although porphyry occurs on the property, the connection does not appear evident unless the sericite-carbonate schist proves to be a highly altered phase of that rock. In the light of present knowledge it appears probable that the mineralizing solutions came from the underlying granite and the localization of the deposits was due to structural control. "In a pure rotational strain the planes (of maximum shear) are about 45° to the shortening or least axis of strain, but the position of the more important one is nearly parallel to the greatest applied pressure or shearing force while the other is 90° or steeply inclined to it.[4]" In the Rice Lake area, it appears probable that the above-mentioned condition of rotational strain was operative, and if the direction of greatest pressure be considered to lie in a general northwest-southeast direction, and to have affected the

[4] Leith, C. K.: Structural Geology, Revised Edition, 1923, p. 20.

several formations differentially, it will in all probability have produced the following results: (1) The least competent rocks, the fragmental series and the volcanic series, were rendered schistose and relatively tight and impervious, the direction of schistosity or principal shear plane being approximately parallel to the direction of applied pressure. (2) With the more competent greenstone relatively little schistosity was produced, but the rock suffered fracturing in two directions, one parallel to the direction of greatest pressure (northwest) and the other at 90° thereto (northeast), leaving openings which were afterwards utilized by the mineralizing solutions. (3) The porphyry proved to be the most resistant rock, except that along the edges it developed merely a slight schistosity and remained impervious to the invading solutions.

Thus in the sequence of events, there were consequent upon the intrusion of the granite, rotational shearing stresses set up in the intruded rocks which affected the different formations in the manner described above. Then ensued the first period of mineralization forming barren quartz veins in the fractured greenstone together with hydrothermal alteration of the adjoining wallrock as evidenced by the extensive carbonization. The earlier, coarsely crystalline, barren pyrite was probably deposited during this era. This was succeeded by a reopening of the northeastern fissures and the deposition within them of the second generation of dark quartz accompanied by fine-grained pyrite and gold. Although this mineralization was in the main confined to the northeast fractures, some deposition occurred in the northwest veins, especially where crossed by the northeast fissuring, causing the somewhat erratic values of those deposits. Associated with the pyrite-gold deposition there is another of gold in quartz with very little accompanying sulphide; it occurs in northeasterly belts of fissuring and its connection with the pyritic gold mineralization is not yet clearly defined.

A third period of mineralization followed, resulting in the deposition of flat barren stringers of quartz and carbonate in the northeast veins. Lastly, a period (or possibly two) of fractur-

ing, represented by two types of fissures healed by barren quartz, which cuts the pyritic veins. One of these types occurs in some of the northwest veins; it has the same strike but dips southwest; the other, striking nearly north and dipping west, cuts and offsets a vein of the northeast system (No. 16).

The sericite-carbonate schist, a rock whose original nature is as yet uncertain, appears to have had two effects: (1) The tongue-shaped projections of this rock appear to have been points against which the northeast fractures tended to become split and broken up; (2) on account of its impervious nature it appears to have acted as a dam concentrating precipitation in its vicinity.

The only mineral of definitely high-temperature origin noticed in the deposits is albite, which is confined to the earliest barren mineralization of the northwest veins. It is probable, therefore, that deposition took place in the upper or cooler part of the deep vein zone. All the later mineralization appears to be definitely mesothermal.

It is considered that practically all the deposition took place by replacement of country rock along narrow openings, since there are no drusy cavities, crustification, or other evidence of the filling of open fissures.

SUMMARY.

The rocks of the Rice Lake area are all of pre-Cambrian age, and in the vicinity of the San Antonio Mine comprise diorite porphyry, greenstone, sericite-carbonate schist, a fragmental and a volcanic series. The porphyry and the greenstone are intrusive and are both younger than the fragmentary and volcanic series, the porphyry being the latest and the volcanic series the oldest formation. The sericite-carbonate schist is a rock of doubtful origin; it is assumed to be of igneous origin and may possibly be a highly altered phase of the porphyry or some similar rock. All these formations are underlain, flanked and intruded by granite, also of pre-Cambrian age.

Consequent on the granite intrusion, rotational stresses affected the invaded rocks, producing fracturing in the greenstone and schistification in the other rocks, thereby making the former the

favorable host for the ore deposits. The fracturing was accompanied or followed by mineralizing solutions emanating in all probability from the same magmatic source as the granite. The solutions caused extensive carbonization of the greenstone and deposited quartz, albite, carbonate, pyrite (two generations), gold and rarely chalcopyrite in the fissures.

There appear to have been four eras of fracturing and five or possibly six of mineralization, of which at most only two produced valuable deposits. Of these, one resulted in the deposition of gold accompanied by fine pyrite and dark quartz, and the other, of white quartz and gold with relatively little sulphide. The pyrite-gold mineralization was preceded by an earlier barren deposition of white quartz and coarse pyrite, and succeeded also by the deposition of white quartz and carbonate, also barren. The relationship of the two kinds of valuable metallization is as yet unknown.

Three types of auriferous deposits are known: (1) Pyritic quartz veins that strike northwest and dip northeast. These are irregular stockwork-like bodies, locally of considerable width, but with an irregular and spotty distribution of values. These veins on account of their strike and dip are successively cut out at depth by the greenstone footwall. (2) Pyritic quartz veins that strike northeast and dip northwest. These are tabular bodies narrower than the northwest veins but they are richer and carry more consistent values; they tend to be enriched where they approach tongue-like masses of sericite-carbonate schist. These veins, normal to the ore zone, are not affected by the greenstone footwall. (3) A vein carrying gold in quartz with little pyrite. Only one such vein is known. It appears to strike northeast but to be of stockwork-like form similar to the northwest veins. The auriferous deposits in places are cut, and in one instance faulted, by later barren quartz veins. All the vein formation appears to be of replacement origin, since there is no evidence of the filling of open fissures. One mineral, albite, of high-temperature origin, occurs in the earliest barren mineralization of the northwest veins, but all the others noted are definitely mesothermal.

ACKNOWLEDGMENT.

The writer is indebted to the directors of the San Antonio Mines Ltd. for permission to publish this paper, and to Mr. D. J. Kennedy, the mine manager, for the information supplied. Data regarding the general geology of the region were obtained from the map of J. F. Wright of the Geological Survey of Canada.

TORONTO, ONTARIO.

DISCUSSION AND COMMUNICATIONS

THE ORIGIN OF CHROMITE.

Sir: In reply to the criticism [1] by F. E. Keep of my paper entitled "May Chromite Crystallize Late?" [2]: Mr. Keep raises many points, some of them on general principles, some on the validity of my evidence, some on local geology in Rhodesia. I appreciate Mr. Keep's request that I reply, and for this reason I shall take up a few features of the geology of Selukwe that I should have hesitated to touch upon otherwise.

Keep discusses several criteria, and as these are of general application, I consider them first. He says concerning the chromite of the main talc-serpentine mass at Selukwe:

> The chromite occurs in the form of isolated lenses which have been proved during mining operations to cease when followed downwards as abruptly as when followed toward the sides. Many lenses do not outcrop but have been cut by adits driven into the hillsides to open up other lenses which do outcrop. This fact alone is evidence against an origin by replacement.

I consider this no evidence against replacement. Replacement can commonly be proved when there is no evidence of the feeding channels, as witness the succession of minerals by replacement within many ore-deposits, or the isolated crystals containing introduced elements formed by contact metmorphism, or even whole contact-metamorphic ore bodies.

In reply to Keep's statement:

> With regard to Figs. 2 and 3 of Mr. Sampson's paper, similar occurrences of chromite-rich enstatite-dunite serpentine occur in the hanging and footwalls of the chromite seams in the Great Dyke of Southern Rhodesia. That these regular seams were formed by replacement is almost unthinkable, as is apparent to anyone who has studied the occur-

[1] ECON. GEOL., vol. 25, pp. 219–221, 1930.
[2] ECON. GEOL., vol. 24, pp. 632–641, 1929.

rences. As for the statement that 'the chromite-free portion is dunite partly altered to serpentine, but that in the chromite-bearing portion serpentinization is complete,' surely that fact cannot be advanced as proof that the chromite is younger than the dunite. Rather is the complete serpentinization near the chromite due to the fact that owing to the difference in competence between the chromite-poor and the chromite-rich dunite, any earth movement would naturally cause an incipient fracturing between these two types, thus affording an easier path for the serpentinizing waters along the edges of the chromite-rich dunite. Or so it appears to me.

If the "seams" to which Keep refers in the "great dike" are *regular*, they are not like my illustrations. I would call attention to the fact that the concentrations of chromite in the rock illustrated form a sort of network not at all in keeping with the distribution of any separate phase (solid or immiscible liquid) present as such in the magma before the crystallization of the olivine. Furthermore, these concentrations consist of scattered crystals of chromite and there is no sharp boundary between chromite concentration and chromite-free silicate. The irregular nature of this boundary and the intricacy of the mesh-work system of the concentrations are not in accord with the view that serpentine accompanies the chromite because of inherent weakness on a major continuous chromite-silicate boundary. However, I regard the distribution of the chromite in the specimen as more compelling evidence of its late origin than the association with serpentine, and I wish to emphasize this feature.

With respect to my statement regarding the Selukwe deposits, Mr. Keep is not following my argument. His discussion is concerned largely with the chromite of the main talc-serpentine area, whereas my remarks were specifically limited to certain offset deposits in conglomerate.[3]

The great deposits of Selukwe [4] are in a geological setting such that the details of origin must remain for the most part obscure, due to the intensity of the metamorphism of the enclosing rocks. These rocks are mostly talc-carbonate schist and serpentine, partly

[3] *Op. cit.*, p. 635.

[4] Zealley, A. E. V.: The geology of the chromite deposits of Selukwe, Rhodesia. Trans. Geol. Soc. So. Africa, vol. 17, pp. 60–74, 1914.

surrounded by intrusive granite. The chromite ore bodies favor the marginal part of the schist area. Of particular scientific interest are certain offset deposits of chromite lying in conglomerate near the talc schist boundary. It is to these offset deposits that I refer in my original paper,[5] and Keep's extended discussion of the ore bodies within the talc-serpentine area is mostly aside from the point.

In 1929 I visited the localities that Zealley described, through the kindness of Mr. Geoffrey Musgrave, Consulting Engineer of the Rhodesia Chrome Mines, Ltd. I wish to express my indebtedness to Mr. Musgrave for his hospitality and assistance. Without his interest and help I should not have found the critical localities.

I quote in full Zealley's careful description, which seems to have been generally overlooked, and I quote also his conclusions as to origin:

> Two interesting occurrences of chromite which are difficult to account for are those in the Conglomerate near the Dunraven and Chrome Mines. In both instances the occurrences are in the immediate proximity of large chromite bodies lying in the Talc Schist. The occurrence to the southwest of the Dunraven Mine is a large solid body of compact close-grained chromite lying in the conglomerate fifty yards or less from its margin. This body is some 150 feet long and three to four feet wide. Actually it appears to be surrounded by a very small thickness of talcose schist (in places not more than a few inches). The conglomerate and grit matrix are pronouncedly green-colored, and contain chromite particles. Alongside this body are also remarkable streaks and narrow parallel bands of more or less closely aggregated crystals and fragments of chromite intermixed with quartz grains of the grit in which it occurs, and of grains and aggregates of chromite interstitial to brecciated pebble-like fragments of various rocks. In the conglomerate also, near by to the south, are small isolated pebble-like and lenticular fragments whose appearance is identical with that of a body of imperfectly segregated chromite which lies near by in the Talc Schist. The occurrence near the Chrome Mine is at the margin of the Talc Schist. There are three or four large bodies of chromite. The conglomerate at its junction with the chromite is colored green, and apparently brecciated. In it abundant isolated crystals of chromite occur interstitially to the pebbles, and a good deal of green (?) talcose material accompanies it.

[5] *Op. cit.*, pp. 633–634.

This chromite in the conglomerate is obviously not of detrital origin since the conglomerate is older than the chromite. Its occurrence possibly might be explained by folding and brecciation of the two formations or by transference of matter from the original magma during its intrusion (contact-metamorphic replacement); the large mass near the Dunraven might even be an intrusive apophysis. There are individual occurrences of those named which appear to demand respectively each one of these theories of origin, but sufficient evidence was not obtained in any instance to arrive at definite conclusions.

To sum up Zealley's observations:

1. Near the Dunraven mine a lens of chrome ore is, at least in the exposed section, entirely surrounded by conglomerate.

2. At the Chrome mine (now known as Kindrade's claims) chrome ore lies between schist and conglomerate.

3. At both places the conglomerate next to the chrome ore is impregnated with scattered chromite crystals forming an aureole, and in this zone of disseminated chromite is a good deal of "green (?) talcose material."

Both workings disclose massive chrome ore, but at neither place is the boundary between ore and conglomerate now disclosed. Weathering is deep, and the conglomerate must be studied by the abundant residual blocks. Two types of material can be secured for detailed study, the massive ore and conglomerate with scattered chromite grains. Near the Dunraven mine ore and country rock are highly sheared. At Kindrade's claims little shearing has taken place.

Sections of the ore from both localities show euhedral to subhedral grains of chromite set in a matrix composed mostly of cherty quartz which in places makes more than half of the ore. This matrix shows no sign of any detrital sedimentary material. Where chromite crystals have been broken by shearing, the fragments are embedded in this fine-grained quartz. The ore from the Dunraven mine contains a considerable amount of a green mineral, probably mariposite.

The fine-grained portion of the conglomerate from Kindrade's claims (Fig. 1) shows in thin section angular and subangular fragments, many of which are feldspar, set in a very fine-grained matrix of quartz. Through this matrix are scattered chromite

grains, many of which are rather sharply angular. Some chromite clearly embays quartz fragments, though this occurs only to a very minor extent. Throughout the rock are rhombs of "limonite" which undoubtedly have formed by the alteration of carbonate.

The conglomerate from near the Dunraven mine (Fig. 2) is

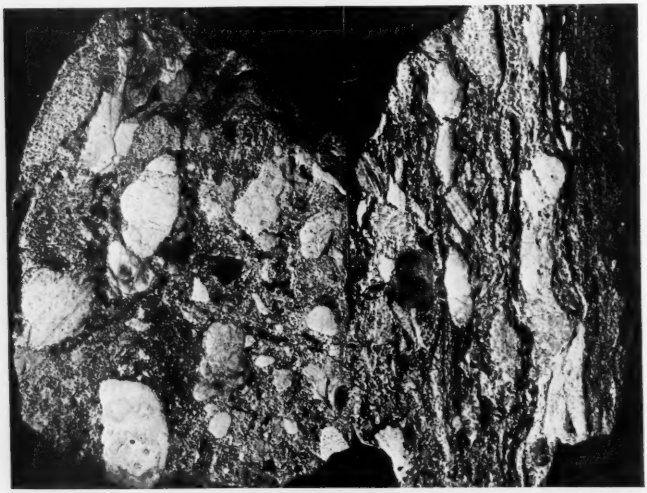


FIG. 1 (left). Chromite in arkosic conglomerate. Kindrade's claims, Selukwe, Southern Rhodesia. × 0.5.

FIG. 2 (right). Chromite with mariposite in sheared arkosic conglomerate. Near Dunraven mine, Selukwe, Southern Rhodesia. × 0.5.

strongly sheared, as is also the chrome ore. Sections of the conglomerate show much crushing and tailing out of both silicate fragments and chromite. The matrix is largely very fine-grained quartz, as at Kindrade's claims, but in addition much mariposite [6] has formed. This appears to be Zealley's "talcose material." The mariposite occurs in bands and wisps following the schistosity. Although mariposite occurs without chromite, practically

[6] Although very fine grained, this determination is fairly satisfactory, being based on optical tests on material separated by heavy liquids and on a partial chemical analysis kindly made by Professor A. H. Phillips. The analyzed material, which

no chromite occurs without surrounding mariposite. Both mariposite and quartz fill fractures in chromite. From the relations it is not possible to say whether the mariposite is distinctly later than the chromite or essentially contemporaneous with it; the latter is possible.

If the chromite has not been introduced into the conglomerate, it must have been laid down with it. Against the placer origin several strong arguments can be cited:

1. Zealley pointed out that the conglomerate is older than the intrusive ultrabasic rocks from which the talc and serpentine schists were formed, and that there is no known possible source for detrital chromite.

2. The lenses of solid chrome ore show no associated heavy minerals such as would be expected in a black sand, in fact they are mineralogically strikingly similar to the chrome ores of the main talc-serpentine area.

3. In the conglomerate containing disseminated chromite there are no fragments of material which could have come from a terrane supplying chromite. On the contrary, the prevailing rocks are vein quartz, acid volcanics, and some ironstone (ferruginous chert).

4. The distribution of the chromite throughout the unsheared

was screened, before separation, between 60 and 80 mesh sizes, contained a moderate amount of intergrown chromite and quartz. The following analysis indicates that the mineral is not talc and that it is in all probability mariposite. It is pale green in thin section and moderately pleochroic.

PARTIAL ANALYSIS OF MARIPOSITE.

A. H. Phillips, analyst.

	Mariposite-rich Fraction from Conglomerate	Theoretical Composition of Muscovite
SiO_2	58.76	45.2
$Al_2O_3 + Fe_2O_3 + Cr_2O_3$	28.96	38.5
CaO	.56	——
MgO	1.63	——
K_2O	6.09	11.8
H_2O	3.74	4.5
	99.74	100.00

conglomerate (Fig. 1) is too scattered to be in accord with deposition by running water, considering the difference in specific gravity between the chromite and silicate fragments, even if all allowance be made for the extremely unsorted nature of the arkosic conglomerate.

Keep advocates an early immiscible chromite liquid, as follows:

> I believe that the deposits represent segregated chromite which occurred in the ultrabasic magma before its intrusion, as suggested by Vogt in his work upon various irregular deposits of chromite and magnetite in Europe. The segregation must be supposed to have taken place in the magma chamber, the molten chromite and peridotite being injected contemporaneously. In those portions where the chromite liquid was on the edge of the intrusion a local replacement of the conglomerate and grit mentioned by Zealley may well have taken place.[7]

In the passage above quoted, Keep is in error in interpreting Vogt's work. Vogt did show that chromite may separate early, but this early separation is in the form of crystals and not a liquid.

If the chromite be considered to have separated as an immiscible liquid before the intrusion of a peridotite magma, the difficulty presents itself that there is no evidence of the effects of the high temperature that we would expect the liquid to have had. C. S. Ross has pointed out clearly [8] the difficulties inherent in assuming the existence of such an early-formed immiscible liquid, and they need not be repeated here. Suffice it to say that the conglomerates at Selukwe adjacent to the chromite lenses show no effects of high temperature metamorphism.

In so far as the deposits are to be regarded as magmatic, I believe that they have been formed from solutions which came into being at a late magmatic stage rather than an early one.

My final conclusion with regard to the Selukwe offset deposits is that the massive chrome ore has formed not by replacement of

[7] Keep, F. E., *op. cit.*, p. 220. Keep concludes his remarks quoted above by saying: "This is not evidence in favor of the view that the lenses of chromite as a whole are younger than the enclosing serpentine and talcified peridotites." This statement is based on a misapplication of my argument. I specifically confined my remarks to the offset deposits.

[8] Ross, C. S., ECON. GEOL., vol. 26, pp. 540–545, 1931.

the rock but by displacement, as is commonly the case with lenticular veins. The chromite in the conglomerate I believe was introduced by solutions of intermediate temperature. The microscopic evidence is mostly of a negative character and rather inconclusive, but the field evidence, as set forth by Zealley, furnishes strong support to this view.

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A LEAD–ZINC DEPOSIT AT GENEVA LAKE, ONTARIO.

Sir: In a recent number of this journal,[1] Mr. Ralph Tuck described the geology and genesis of the mineral deposit operated by the Lake Geneva Mining Co., Ltd., at Geneva Lake, Ontario. He concluded that the country rock is the metamorphosed Serpent formation of the Bruce series (of Huronian age). He cited a paper by me [2] in support of his contention that the mineralization was from the magma that gave rise to the ubiquitous sills and dikes of diabase. If his conclusions are correct, the Bruce and Cobalt series of this area merit careful prospecting; however, I have given reasons [3] for believing that the metasomatic deposits found in the Huronian rocks near the diabase are likely to be small and of much less importance than those, such as the Geneva Lake Mines, contained within the pre-Huronian gneisses and schists.

I should like to review briefly my reasons for believing that the country rock is pre-Huronian and that the mineralization is derived from a granite rather than a diabase magma.

The elongated area of the pre-Huronian gneisses and schists consists predominately of hornblendic rocks, which have an east-west strike and a steep southerly dip. Meta-sedimentary

[1] ECON. GEOL., vol. 26, no. 3, pp. 295–313, May, 1931.

[2] A Diabase Contact Metamorphic Mineral Deposit in Ontario. ECON. GEOL., vol. 24, pp. 722–732, 1929.

[3] The Cartier-Stralak Area, District of Sudbury. Ontario Dept. of Mines, Ann Rept. 38, pp. 52–68, 1930.

rocks outcrop in an elliptical area extending from Moncrieff township into the southwest corner of Munster township. These rocks are considerably metamorphosed and appear to have been deformed, in part, with the gneisses and schists. Some of them extend nearly to the Geneva Lake Mines. The pre-Huronian rocks have been extensively granitized by a granite outcropping to the north. A "transition zone"[4] separates the granite and schist. The zone extends as far south as the Geneva Lake Mines, and the gneisses and other rocks formed there have complicated structures that make it difficult to determine their relationships.

The age of the mass of granite north of the belt of gneisses and schists was not determined in the Cartier-Stralak area; however, all the granites that could be dated are pre-Huronian, and the granites forming "transition zones" against similar pre-Huronian rocks in the Onaping[5] area to the north are pre-Huronian. This granite is therefore believed to be pre-Huronian.

The Huronian rocks, consisting of the Bruce and Cobalt series, strike northwest and are infolded and infaulted into the older formations. At one place a few hundred feet north of where the road to the Geneva Lake Mines branches from the tote-road to the Onaping River, the pre-Huronian rocks metamorphosed and cut by many granite and satellitic dikes, are separated from the Gowganda formation by a fault. The strike of the two formations is at a considerable angle, and the dikes do not cut the Gowganda formation. Although this is not conclusive evidence for the pre-Huronian age of the formation at the Geneva Lake Mine, it is highly suggestive of it because the Bruce and Cobalt series elsewhere in the area are not separated by important igneous intrusions. Rocks known to belong to the Bruce series were not found cut by granite in any part of the Cartier-Stralak area.

Mr. Tuck described the breccia occurring near the base of the Serpent formation and outcropping near the vein of the Geneva Lake Mines. Mr. W. E. Bawden, superintendent for the Geneva Lake Mining Company, drew my attention to the "basal con-

[4] Osborne, F. F.: A Schist Granite Transition Zone in Ontario. Jour. Geol., vol. 38, pp. 75–80, 1930.

[5] Collins, W. H.: Onaping Map-area. Geol. Surv. Can. Mem. 95, 1917.

glomerate" outcropping on the south slope of the hill north of the powerhouse. It consists of angular, subangular, and rounded boulders of considerable variety held in a fine-grained, dark-green matrix in which plagioclase laths are visible. My thin section shows that the matrix is a chilled diabase, in which the minute phenocrysts are calcic feldspar, augite, and olivine. Whether the rock would give rise to the quartz diabase or the olivine diabase on slow cooling cannot be told. Similar breccias with a chilled diabasic matrix are not rare in the area and are probably due to the magma advancing along the zones of faulting. In fact, many of the larger intrusions of diabase occur along fault zones. Near the Geneva Lake property this zone is approximately parallel to the rather complicated structure but in other places, for example on the railroad near Benny, it cuts across the structure.

Some basic dikes cut the Huronian rocks, but most dikes are found in the older rocks. The dikes are probably of different age. Some are probably pre-Huronian. Many are post-Huronian. The younger dikes are olivine diabase. The quartz-diabase has been responsible for some mineralization: the contact metamorphic deposit in Hart township mentioned above is the most important example; other occurrences of magnetite, specularite, sphalerite and pyrite are known. The occurrences are invariably small and quite close to or within the quartz diabase. On the other hand, the Geneva Lake Mines are the principal representative of a more important group of mineral deposits, which occur in the gneisses and schists. They are found in the northern part of the pre-Huronian band. The other important property of the area is near Stralak and is owned by the Sudbury Mining and Concentrating Company, Ltd. The vein and mineralization are similar to those of the Geneva Lake Mines, and outcrops are found at intervals over 6,000 feet. Several smaller occurrences of pyrrhotite, sphalerite, and galena are found in the same general zone. The distance from the granite contact is about the same in all cases, and the degree of metamorphism of the enclosing rocks is the same. Some of the veins are cut by dikes of quartz

diabase and other veins appear to cut altered diabase dikes. The relationship of the deposits to the granite contact, and the fact that known instances of mineralization from the quartz diabase are close to bodies of the diabase and are small, suggest that these larger deposits were formed by emanations from granite that formed the transition zone to the north.

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REVIEWS

Magnetite Deposits of French Creek, Pa. By LAURENCE L. SMITH. Pennsylvania Top. and Geol. Survey, Bull. M 14. Pp. 52, pls. 5, figs. 5. Harrisburg, 1931. Price, 25c.

In the days when the Alleghenies were America's western frontier, much of her metal production came from deposits associated with the series of diabase intrusions extending from New England to Virginia. Of most importance in relatively modern times have been the iron deposits but of these only Cornwall, Pa., has survived. A smaller deposit of the Cornwall type was reopened during the War but was closed down again three years ago. It is fortunate for geologists that data for an excellent description of it were collected by Mr. Smith while the workings were still accessible. Mineralogists, too, will welcome this information regarding a celebrated locality that is represented by spectacular specimens in every important collection in the country.

After presenting a thorough areal and petrographic study of the geology of the vicinity, the author describes the structure of the ore body, a replacement lens in pre-Cambrian (Franklin) limestone adjacent to the diabase. A paragenetic study shows that, as in many pyrometasomatic deposits, the "skarn minerals" (in this case, garnet, augite and actinolite) are earlier than the ore and separated from it by a period of formation of hydrous silicates.

The author believes that the ore magma (sic) is a late-stage differentiation product of the *deeper diabase magmatic reservoir*, basing his conclusion on the existence of unreplaced portions of the limestone lying against the diabase, and on the presence of pegmatitic dikes which cut the intrusive and are considered closely related to it in origin. At Cornwall, on the other hand, Callahan and Newhouse[1] regard the ore-bearing solutions as originating in the *immediately adjoining* diabase. In view of the similarity of French Creek to Cornwall, the contrasting interpretations, characteristic of two schools of thought which prevail today regarding contact deposits in general, may perhaps be attributed to the difference in the respective backgrounds of their authors rather than to any inherent difference in the origin of the ore bodies themselves. H. E. MCKINSTRY.

[1] W. H. Callahan and W. H. Newhouse: A Study of the Magnetite Orebody at Cornwall, Pa., ECON. GEOL., vol. 24, p. 403, 1929.

Economic Geography of Europe. By W. O. BLANCHARD AND S. S. VISHER. Pp. viii + 507, figs. 330. McGraw-Hill Book Co., New York, 1931. Price, $3.50.

While not dealing directly with any phase of geology, this book by Blanchard and Visher is a convenient brief summary of the characteristics of each of the countries of Europe, from historical, political, industrial and commercial standpoints. It is of most interest to geologists because of its brief, but comprehensive, outline of the mining industries of the various countries and of the industries utilizing mineral products. The book is illustrated by many diagrams and graphs and by photographs of characteristic topography. Its emphasis is largely on the physiography of the different countries and their trade relations.

The book is interesting, is well printed, and is bound in the substantial manner characteristic of recent books by the same publisher.

W. S. BAYLEY.

Geology of Petroleum. (Second Edition.) By WILLIAM HARVEY EMMONS. Pp. 736, figs. 435. McGraw-Hill Book Company, New York, 1931. Price, $6.00.

This book is far from being merely an enlarged edition of Emmons' Geology of Petroleum, which was first published in 1920. If it were only that, it would be well worth a place in the library of every oil geologist, but as it is, it would seem to be an almost indispensable book of reference. It is particularly interesting to note that the author has kept abreast of the gradual relinquishment of certain ideas as well as of the newer developments in oil geology. For example, in the first edition, he devotes three pages to a discussion of the inorganic theories of the origin of oil; in this edition he disposes of them in fifteen lines.

The plan followed in the text is similar to that of the first edition although a great deal of the material is new. Its introductory part, dealing with surface indications, reservoir rocks, the properties and origin of petroleum, is reduced to 72 pages. The chapters dealing with accumulation and structural features occupy 80 pages.

In discussing the oil fields of the United States, the author does not depart from his original grouping of the fields into geographical rather than tectonic provinces, except that he groups all the fields east of the Mississippi River into a single chapter of 77 pages. His description of the Mid-Continent area is 192 pages in length as opposed to 86 in the first edition, the Gulf Coast, Rocky Mountain and California areas being given, respectively, 29, 70, and 48 pages. In his description of foreign fields, he shows his appreciation of their growing importance.

Because of the amount of detail which the author has managed to compress into this volume and the very imposing list of references furnished, the reviewer considers it to be more valuable as a reference book than as a text for class use, especially since such a compilation must necessarily contain a great deal of repetition.

The publishers are to be congratulated on the way in which the book has been printed, as in this regard it is a distinct improvement over other texts which have been published recently.

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The Japanese Earthquake of 1920. By CHARLES DAVISON. Pp. 127, figs. 32, pls. 6. Thos. Murby & Co., London, 1931. Price 7s. 6d.

This little book gives a brief but clear account of the great earthquake that caused the fire which destroyed Tokyo in 1923. It is a summary of the numerous official and private Japanese publications dealing with the event and its consequences. Its first part deals with the earthquake as it affected man and his works, and the second part with the quake as a geological phenomenon. The shock was not one of the first magnitude, since it was felt over an area of only 166,000 sq. miles, whereas the shock of 1891 was felt over 330,000 sq. miles and the San Francisco earthquake over 373,000 sq. miles. After discussing the intensity and nature of the earthquake motion, the position and depth of its focus and the velocity of propagation of the elastic wave, the geological effects are outlined in some little detail. After a thorough examination of the area that was shaken, it has been found that on the land the maximum vertical elevation was 6 ft. 6 in., near the town of Koda, on the west side of Sagamic Bay, and the same near Mera, on the Boso Peninsula. The maximum subsidence was 5 ft. 4 in., at a point 14 miles northwest of Kodu. Along the coast the elevations were at places sufficient to greatly change the configuration of the coast lines, and in many places there was a permanent uplift great enough to raise wave-cut terraces seven feet above the sea-level, thus exposing at the bases of some cliffs platforms several hundred yards in width. Horizontal displacements as great as 9 feet have been observed. The movements have been such as to suggest that the whole district around the epicentrum has received a clock-wise twist. The dislocation of the sea-bed was remarkable. There were subsidences of various magnitudes up to 1554 feet and nearby elevations of 820 feet. The total area of subsidence was 270 square miles and of elevation 90 square miles. The maximum movements appear to have been along the two sides of a down-thrown block, which on the land appears to have given rise to a rift-valley.

On the land numerous small faults were produced with vertical displacements between 8 inches and 6½ feet. At one place is exposed a shatter-zone from 55 to 550 yards wide consisting of 20 or more parallel faults with scarps about 1 foot high, separating blocks the upper surfaces of which are gently sloped in one direction.

The volume contains no fine writing. It is simply a good record of what the Japanese geologists have learned about the earthquake, and as a summary it is very satisfactory. It would have been much more satisfactory, however, were the maps not so poor. None of them are provided with legends, and many of the places referred to in the text are not represented on them. Although the shock is known as the Kwanto earthquake, even this name does not appear on the general map.

W. S. Bayley.

Biennial Report of the State Geologist of Missouri, 1931. Pp. 151, pls. 14. Rolla, Mo., 1931.

This report is of unusual interest because it contains in addition to the work of the Bureau, and the mineral production of Missouri, a noteworthy paper (pp. 102–145) on "Insoluble Residues as a Guide in Stratigraphic Studies" by H. S. McQueen. This paper shows that the insoluble residues of the Missouri formations contain characteristic features that afford a basis for correlation of non-fossiliferous beds cut in drill holes. The most noteworthy of these features are the so-called "dolocasts" or chert fragments with casts of minute dolomite crystals. Other characteristic forms are also described. The results are striking and tests show that correlation can be made over wide areas with certainty. This work provides not only a definite means of correlation of great value in oil, water, and ore drilling, but also is of value in other fields, such as sedimentation and paleography, by giving the location of unconformities. Correlations have been carried across the whole state of Missouri and even with some Wisconsin rocks. Dr. Buehler is to be congratulated for the valuable work his Survey is giving to scientific and economic geological studies.

Another interesting appendix is on "Geophysical Prospecting." The Bureau has conducted field work by magnetic and electrical resistivity measurements and these have disclosed the depth of bed rock, faults and unexposed sink holes, etc. The value of such work is evident for bridge building, highway construction, water supply, and subsurface geology. This report should be read by all geologists.

Alan Bateman.

BOOKS RECEIVED.

Surface Water Supply of the United States, 1927. *Pt. I:* No. Atlantic Slope Drainage Basins. Pp. 188, fig. 1. U. S. Geol. Surv. W. S. Paper 641, 1931. Price, 35 cts. *Pt. III:* Ohio River Basin. Pp. 216, fig. 1. U. S. Geol. Surv. W. S. Paper 643, 1931. Price, 35 cts.

Geology and Ground-Water Resources of Western Sandoval County, New Mexico. By B. C. RENICK, in coöperation with the State Engineer of New Mexico. Pp. 117, pls. 10, figs. 3. U. S. Geol. Surv. W. S. Paper 620, 1931. Price, 35 cts.

Geology of the Big Snowy Mountains, Montana. By F. REEVES. Pp. 15, pls. 4, fig. 1. U. S. Geol. Surv. Prof. Paper 165–D, 1931. Price, 20 cts.

Limits of Inflammability of Gases and Vapors. By H. F. COWARD AND G. W. JONES. Pp. 114, figs. 36. U. S. Bur. of Mines Bull. 279, 1931. Price, 20 cts.

Economics of Crushed Stone Production. By O. BOWLES. Pp. 62, figs. 49. U. S. Bur. of Mines, Econ. Paper 12, 1931. Price, 15 cts.

Analyses of Washington Coals. Pp. 203, fig. 1. U. S. Bur. of Mines, Tech. Paper 491, 1931. Price, 30 cts.

Bibliography of United States Bureau of Mines Investigations on Coal and Its Products, 1910–1930. By A. C. FIELDNER AND M. W. VON BERNEWITZ. Pp. 56. U. S. Bur. Mines Tech. Paper 493, 1931.

The Mineral Industry of New Jersey for 1929. Pp. 29, pls. 3. State Dept. Cons. and Devel. Bull. 36, Geol. Ser. Trenton, 1931.

Spectrum Analysis in Mineralogy. By A. A. FITCH. Pp. 52, figs. 8. Adam Hilger, Ltd., London, 1931. Price, 1s 9d, postpaid, 1s 11d. Technique of analyzing minerals, rocks, and waters. Tables of minerals analyzed with elements detected. Surprising number of elements in the common minerals.

Investigations of Mineral Resources and the Mining Industry (Canada), 1929. Pp. 69. Canada Dept. of Mines, No. 719, Ottawa, 1930. Contains the following papers: Wilberforce Radium Occurrence, by H. S. SPENCE AND R. K. CARNOCHAN; Notes on Anhydrite, by L. H. COLE AND R. A. ROGERS; Bituminous Sands of Northern Alberta, 1929, by S. C. ELLS; Limestone in Industry, and Limestones of British Columbia, by M. F. GOUDGE.

Investigations in Ore Dressing and Metallurgy (Canada), 1929. Pp. 208. Mines Branch, Canada Dept. of Mines, No. 720. Ottawa, 1931.

The Mining Laws of Canada: a Digest of Dominion and Provincial

Laws Affecting Mining. Pp. 98. Canada Dept. of Mines, No. 713. Ottawa, 1931. Price, 25 cts.

Report of the Director, Geological Survey of Southern Rhodesia, 1930. Pp. 13. Salisbury, 1931.

A Industria do Sal no Estado do Rio (Brazil). By M. DA S. PINTO AND R. R. FILHO. Pp. 143, figs. 48, maps. Rio de Janeiro, 1930.

An Economic and Commercial Geography of India. By B. B. MUKHERJEE. Pp. 166. Thacker, Spink & Co., Calcutta, 1931. Price, 6s 2d.

Geology of the Potosi and Edgehill Quadrangles (Missouri). By C. L. DAKE. Pp. 233, pls. 26, maps 2. Missouri Bur. Geol. and Mines, vol. 23, 2d ser., 1930, Rolla, 1931. Good discussion of general geology, stratigraphy and structure; deposits of barite, lead, zinc, iron, clay, gravels, building stones, and water.

Geology of the Eminence and Cardareva Quadrangles (Missouri). By J. BRIDGE. Pp. 228, pls. 22, figs. 10, tables 2, maps 2. Missouri Bur. Geol. and Mines, vol. 24, 2d ser., 1930, Rolla, 1931. Thorough study of physiography, particularly affecting water supply; detailed stratigraphy (also systematic paleontology) and structure; treatment of deposits of copper, iron, manganese, lead, sand, gravel, clay, building stone, and water power.

The Examination of Fragmental Rocks. By F. G. TICKELL. Pp. 127, figs. 51. Stanford Univ. Press, 1931. Price, $5.00. The bulk and grain properties of fragmental mineral aggregates and rocks. The chapter headings are: I, Size analysis; II, Porosity and permeability; III, Preparation of specimens; IV, Identification of minerals; V, Description of minerals found in sedimentary rocks.

Katalog der Bibliothek, Deutsche Geologische Gesellschaft. By P. DIENST. Pp. xi + 1161. F. Enke, Stuttgart, 1930 (1931). Price. 70 M. Catalog of the library by authors, arranged under larger geologic subjects with numerous subdivisions. Invaluable to investigators; also extremely convenient as a bibliography.

The Quantity and Sources of Our Petroleum Supplies. By J. M. MACFARLANE. Pp. 250, pls. 5, figs. 9. Noel Printing Co., Phila., 1931

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

H. Foster Bain has returned to New York City after a trip to Europe.

Parker D. Trask, who has been connected with the Frick Laboratory at Princeton University, has joined the staff of the U. S. Geological Survey.

V. H. Gottschalk, senior physicist of the U. S. Bureau of Mines, has taken the place of J. D. Sullivan, recently resigned, in the Bureau of Mines station at Tucson, Arizona.

E. T. Mellor, after a visit in London, has returned to Johannesburg and will open a consulting office there.

K. Y. King, of the Chinese Geological Survey, has been visiting the United States.

W. H. Twenhofel, of the University of Wisconsin,who is on sabbatical leave, has taken the place of Arthur Keith as chairman of the Division of Geology and Geography of the National Research Council.

Anton Gray, geologist of the Mufulira Mine, Northern Rhodesia, has returned to Africa after a vacation spent in England.

D. D. Irwin, general manager of the Roan Antelope Mine, Northern Rhodesia, is making a visit to the United States and is at present in South Carolina.

Percy G. Dobson has returned from work in Mexico to the United States, and is now in El Paso, Texas.

W. R. Hobbs, of the department of geology, University of Michigan, is attending the International Geographical Congress in Paris and will join an excursion to the Sahara.

Paul A. Schafer is to take the place of E. S. Perry as assistant professor of geology at the Montana School of Mines, while the latter engages in special work.

W. T. Nightingale, geologist for the Mountain Fuel Supply Company, is credited with the discovery of the Powder Wash gas field in northern Colorado, with a flow of a million cubic feet in the discovery well.

R. G. Picher, of the Canada Department of Mines, Ottawa, has been making a detailed examination of gravel and sand deposits in eastern Quebec, with a view to their use in road construction and concrete.

Lawrence B. Wright has resigned as chief geologist of Homestake Mining Co. and has taken up general consulting practice. He has lately been directing development at Double Rainbow Mines, Galena, S. Dakota.

Robert Tally, president of the A. I. M. E., gave an address at the dedication of the new engineering building of the Michigan College of Mining and Technology, August 6 to 8.

F. E. Johnesse and W. G. Huseman have organized a clearing house for buyers and sellers of mining properties, the Western Mines Agency, with offices at Boise, Idaho. Monthly lists of available properties will be compiled.

J. R. Van Pelt, formerly curator of the Division of Geology and Mineral Industries, Chicago, is acting director of the Rosenwald Museum of Science and Industry and assistant director in charge of Technology.

D. A. Lyon, of Salt Lake City, Utah, formerly chief of the U. S. Bureau of Mines station there, is now director of the State Engineering Station and in charge of the State University's mineral industry operations.

L. Don Leet, instructor in seismology at Harvard University, has been studying the velocity of seismic waves in granite at Quincy, Mass., and Westerly, R. I., by means of recording vibrations caused by dynamite explosions.

The optical works of E. Leitz, at Wetzlar, Germany, have completed their 300,000th microscope. In accordance with their custom of presenting every 50,000th instrument to an outstanding scientist, this one was given to Professor Ludwig Aschoff of Freiburg.

John G. Barry, consulting mining geologist and engineer, El Paso, Texas, was recently appointed President of the Texas College of Mines and Metallurgy, a newly instituted office. A change of name is also contemplated later, the Texas College of Mines and Arts. Mr. Barry, who had teaching experience in the University of North Dakota and the Massachusetts Institute of Technology before taking the position of chief geologist with the American Smelting and Refining Company in 1924, will continue consulting practice on a limited scale as far as his college connection permits. Plans are under way for enlarging the college faculty so that a four-year academic course can be given, and it is hoped to make it one of the leading mining schools of the country.

R. A. F. Penrose, Jr., geologist, died suddenly on July 31 at Philadelphia, at the age of 67. Dr. Penrose has at various times been connected with the U. S. Geological Survey and several State Surveys, and was for many years associated with the University of Pennsylvania as a trustee. He made bequests to the American Philosophical Society, the Geological Society of America, the Society of Economic Geologists, and to this journal.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.